THE COASTAL PINE RIDGE SOILS OF BRITISH HONDURAS AND THEIR FERTILITY STATUS

By

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INTRODUCTION

For centuries, man has tried to adjust the face of the earth to suit his particular needs. In doing this, man is in conflict with nature, and primarily with its component factors, namely, climate, soil, and vegetation. These factors are in continuous change.

In agriculture, for successful land development, two main points must be observed:

1) An inventory of soil resources is most needed.
2) The selection and introduction of crops should be made with skill, choosing suitable soil and evolving management methods, if optimum production is expected.

The investigational stage should not be omitted, even though projects may appear simple, and the results must be carefully evaluated to provide adequate recommendations.

British Honduras offers one of the largest areas of undeveloped land for agricultural utilization within the Caribbean Region (159). It presents some special features which may be common to some other equally undeveloped countries. For over 200 years labor requirements for agricultural production suffered owing to more attractive conditions of employment offered by timber exploitation or trading concerns; consequently, labor for agriculture was never cheap nor plentiful. This situation produced small owner-farmers who acquired practical knowledge of farming problems. They may play an important role in becoming the backbone of the agricultural development of the country.

For the purpose of the present investigation, two of the Coastal Alluvial Pine Ridge Soils, also known as the Pulmtan soils, were selected in the vicinity of Belize City, primarily because:

1) The Coastal Alluvial Pine Ridge Soils cover a relatively large area of British Honduras, approximately 2,849 km^2, and are considered by several investigators to be important in the future development of the country regardless of the unfavorable features they possess.
2) The land within a radius of 24 to 32 km of Belize City is fairly well supplied with roads and has two large navigable rivers (Sibun and Belize). Belize City itself is a potential market for most agricultural products and it is utilized as a commercial port for import and export purposes.
3) The knowledge gained through the present investigation may constitute the basis for further studies of soils with similar physical and chemical characteristics encountered elsewhere in the American Tropics, particularly in Guyana and Venezuela.

The objectives of this investigation were the following:

Field work

1) Identification and sampling of representative Coastal Pine Ridge Soils.

Laboratory investigations

1) Physical analyses of selected soil samples.
2) Chemical analyses of selected soil samples.
3) Other laboratory studies related to the fertility status of these soils, namely (i) P-fixation capacity, (ii) mobility

of P in the soil profile, and (iii) soil P availability and plant yields.

Greenhouse investigations

1) Determination of the actual fertility status of selected Fuiatan soils by pot-tests.
2) Study of the responses of crop plants to lime and fertilizer applications, with particular emphasis on the response and uptake of fertilizer P.

REVIEW OF LITERATURE

The Country

British Honduras is situated on the east coast of Central America and lies within latitudes 15° 54' and 28° 29' N and longitudes 83° 10' and 89° 09' W. It is bounded on the east by the Caribbean Sea, on the north and northwest by the Republic of Mexico, and on the west and south by the Republic of Guatemala. In length, British Honduras extends 280 km from the Rio Hondo in the north to the Sarstoon River in the south. In breadth, at the widest part (Belize to Benque Viejo) it is 109 km. The mainland territory of the country totals some 22,965 km^2.

Topography

The chief topographical features of British Honduras are. (1) The flat Northern Plain of low relief, lying north of the latitude of Belize, and occupying more than half of the area of the country, (2) The southern-central Maya Mountains of general altitude 650 m to 1,000 m, containing the Cockscomb Range, 1,230 m high, (3) The low-lying Southern Plain, containing protruding rounded hills, lying west of Punta Gorda, (4) The Coastal Plain, which varies in width from 8 to 16 km and rises to an elevation of 33 m at its western boundary, lies to the east of the mountainous region and forms the coastline of British Honduras south of Belize, and (5) The Cayes and

Coral Reefs, an innermost reef extends nearly the entire length of the coast, 24 to 32 km from the shore, and two smaller reefs lie 48 to 80 km further east. These cayes cover a total area of about 549 km^2.

The main water courses occur in the Northern Plain area, two of which (Belize and Sibun Rivers) arise in the Maya Mountains, and two (New River and Rio Hondo) arise in low hills lying to the west of the Northern Plain. Other rivers, draining the Maya Mountain area, arise from a divide lying about 40 km from the coast. All the main rivers flow eastward into the Caribbean Sea. The Sarstoon River forms the southern boundary of the country, it arises in the mountains of Guatemala.

Climate

Although British Honduras lies in tropical latitudes, the climate is almost sub-tropical. Trade winds and sea breezes persist for nearly nine months of the year. The mean annual temperature is about 27 C. The mean annual rainfall is nearly 2,083 mm; but in the north of the country it averages only 1,524 mm, while in the south, it is over 3,048 mm. A distinct dry season extends from January to May.

Geology

Ower (106) classified the geological formations of British Honduras as follows.

Name of formation	Area (km^2)	Geological Age
(1) Recent Deposits (coral, river alluvium, upland Pine Ridge sands)	--	Recent

	Name of formation	Area (km^2)	Geological Age
(2)	Old Coastal Alluvium (Pine Ridge Formation)	2,849	Post Pliocene
(3)	Toledo Beds	1,683	Miocene
(4)	Rio Dulce Limestones and Marls	13,131	Miocene-Oligocene
(5)	Granitic Igneous Intrusions	958	Permo-Carboniferous
(6)	Slate Series	2,642	Upper-Carboniferous

A brief description is next given of each of these geological formations, proceeding from the oldest to the newest.

Slate series

This is confined to the Maya Mountains and consists mainly of foliated metamorphic rocks, namely, schists and slates, sandstones, quartzites, and blue limestone.

Granitic Igneous Intrusions

Six main outcrops of these rocks have been identified within the country at Mountain Pine Ridge, Middlesex, Silk, Grass Creek, Waha Leaf Creek, Cockscomb, and Rio Bladen. They consist of biotite granite,and porphyry. The granite is intruded into the older Slate Series. The porphyry, mainly occurring south of Swasey River, is a fine grained quartz-felspar rock, forming sills, dykes, lava flows, and ash beds interbedded with the slates.

Rio Dulce limestones and marls

This formation occupies the greater part of the country. It forms the whole of the Northern Plain, extends northward over Yucatan, and contains the rounded conical hills of the Southern Plain west of

Punta Gorda, which are partly overlain by the Toledo Beds. The limestone is composed mainly of foraminifera, though it is frequently crystalline and perhaps dolomitic. It is white or creamy, weathers easily, and has a high calcium carbonate content.

The marly representatives occur only north of latitude 17° and are best developed around Cayo, Orange Walk, and Corozal. The marls appear to lie on the surface of the hard limestones, and are not interbedded with them. It is highly probable that they were derived from erosion of the limestone cap which once covered the whole of the central mountain mass.

The limestone and marl country abounds with relics of the Mayan civilization, including terraces and mounds.

Toledo beds

This formation is confined to the region west of Punta Gorda and is represented by crushed and folded thin-bedded shales and mudstones, interlayered with laminated limestones and blue-calcareous sandstones with occasional diatomites.

Old coastal alluvium

These alluvial deposits, which were geologically recently submerged beneath the sea, form the Coastal Plain around and south of Belize. They comprise materials brought down by the mountain streams, and consist of coarse grits overlying grey micaceous, kaolinitic clayey-sand and silt. The grits are frequently broadly mottled red by iron oxide and set hard when dry.

Recent deposits

These include alluvial deposits in swamps and estuaries, and along the lower reaches of river-courses, where they form levees or riverine strips, usually slightly higher than the swampy coastal-plain land on either side. They are comprised by finely mottled red and white clays often containing grit and gravel, particularly when traced inland.

Vegetation

According to Wright et al. (159) the following are the original formations that once covered British Honduras:

Broadleaf forests rich in "lime loving species".--Mahogany (Swietenia macrophylla) and sapote (Achras sapota L.) are the typical representatives of this type.

Broadleaf forest with occasional "lime loving species".--These are evergreen seasonal forests composed of deciduous species.

Transitional broadleaf forests.--These forests have not reached the climax stage; the soil and vegetation show signs of instability. The forest height is lower than the above types and the canopy is more level. A characteristic species in the shrub layer is the black and white maya (Miconia spp.).

Shrub land with pine.--This is a transitional type in which the soil is only capable of supporting shrubs, but, through the influence of disturbing factors, such as fires, hurricanes, or human activities, pines have had a chance to invade. This vegetation is typical of the Broken Pine Ridge.

Pine forest and orchard savanna.--This is the typical pine savanna.

Marsh and swamp communities.

Coastal formation.

Cohune palm (Orbygnya cohune) forests.--This vegetation area is valued for "milpas" because the soils are regarded as the most fertile of the lot.

Each of the vegetation types indicated was subdivided into several groups which were largely related to available soil moisture.

The woody vegetation associated with pines in the savanna plains is mostly brush, with stiff leathery leaves and thick bark. The most important species are *Curatella americana*, *Miconia* spp., *Byrsonima crassifolia*, *Calliandra houstoniana*, and less commonly *Quercus*, *Crescentia*, and *Mimosa*. The herbaceous plants, *Cyperaceae* and *Gramineae* are prominent. The bunch grasses most conspicuously represented are *Trachypogon*, *Andropogon*, *Paspalum*, *Aristida*, and *Leptoscoryphium*. Along the forest margins, grasses are higher and belong to different species, such as *Arundinella deppeana*, *Ischaemum latifolium*, and *Tripsacum laxum*. They are considered as transitional vegetation between forest and savannas.

It is important to point out that long before soil studies were made in British Honduras, local foresters thought the general trend of plant succession was from savanna grass to pine to broadleaf forest. However, Hardy *et al.* (60), Charter (34) and Wright *et al.* (159) stated that the succession was from broadleaf forest to pine to savanna grass. They considered that such succession is closely connected with the rate and intensity of soil leaching and consequent depletion of available plant nutrients as well as to the development of compact clay subsoils and sandy shallow topsoils. Consequently, the actual pattern of vegetation is very much more complex than originally indicated.

The Coastal Pine Ridge Soils

The Coastal Pine Ridge soils are also known as Puletan soils, a term formerly applied by the Maya Indians to Monkey River where these soils were first mapped. They cover a very large area in British Honduras, approximately 2,849 km^2 from Deep River in the south almost to Orange Walk in the north. They have been mapped over a N-S strip 293 km long and from 8 to 56 km wide. In many places they reach the seashore or are separated from the sea only by a fringe of mangroves. At intervals, the Coastal Plain is broken by the vega soils of rivers draining eastward from the Maya Mountain massif.

Location

In the scheme suggested for the Regional Development of British Honduras, Wright *et al.* (159) described the Puletan soils as comprising two main sub-regions, namely, Coastal Plain and Pine Ridge, which in turn are part of two regions, namely, the East central and the Belize. Each of these two locations will be briefly described.

East central region, coastal plain sub-region

This area of approximately 906 km^2 includes a nearly flat coastal plain extending 64 km from Stann Creek to Deep River in the south. This plain has an average width of 16 km and becomes gently undulating as it approaches the foothills. The rainfall in the area increases from 2,794 mm in the north to 3,810 mm in the south The soils on this plain are formed from old coastal deposits. They are much leached in the topsoil and have an impervious acid subsoil. Low fertility and poor internal drainage are the chief limiting factors.

Belize region, pine ridge sub-region

Belize is surrounded by a large area of Puletan soils that cover a total area of approximately 1,554 km^2. The whole area is mainly flat in topography with an average annual rainfall of 1,534 to 2,032 mm. The soils are also of low fertility with poor internal drainage.

Climate

Mean monthly rainfall, mean, maximum, and minimum temperatures, and mean potential evapotranspiration for the 10-year period 1957-1967 are presented in Table 1 and depicted in Fig. 1. According to these data, the climate in the Belize area is hot with two marked seasons. It is continuously dry, when potential evapotranspiration exceeds rainfall from December to May, and almost continuously wet from June to November with a short dry period in August. Temperature fluctuations seem to run parallel to rainfall and are uniform only during the rainy season.

Vegetation

The natural vegetation covering the Coastal Pine Ridge soils may well have been a light forest with Oak (*Quercus* spp.) *Clucia* spp., especially *Clucia massoniana*, *Leucothoe*, *Tapirira*, and other species now seldom encountered.

At present, savanna grasses and sedges form the plant cover over most of the Coastal Plain. These are chiefly *Andropogon* spp., *Eragrostis maypurensis*, *E. spectabilis*, *Panicum laxum*, *P. plicatulum*, and *Sporobolus indicus* among the grasses, and *Cyperus* spp. and *Scleria ciliata* among the sedges. Pine forests are likely to occur on most parts of the plain except where the land is quite flat or

Table 1.--Climate of Belize City, 1957-1967 (10-year averages).

		Temperature				
Month	R	Mean	Max.	Min.	E-T	SR
	mm	-----------	C	----------	----- mm	-------
Jan.	110.0	22.9	27.2	18.7	144.4	- 34.4
Feb.	70.5	24.2	28.2	20.2	149.1	- 78.6
Mar.	48.7	23.8	27.7	19.9	147.5	- 98.8
Apr.	93.5	26.0	29.9	22.2	155.6	- 62.1
May	68.2	22.6	26.6	18.7	143.4	- 75.2
Jun.	206.5	27.4	31.2	23.7	160.5	+ 46.0
Jul.	245.0	27.0	30.7	23.4	158.9	+ 86.1
Aug.	137.7	27.1	30.9	23.3	159.4	- 21.7
Sep.	214.5	27.2	30.9	23.5	159.8	+ 54.7
Oct.	235.2	25.3	30.1	20.5	152.9	+ 82.3
Nov.	155.7	25.2	29.1	21.2	152.3	+ 3.4
Dec.	138.5	24.2	28.0	20.5	149.1	- 10.6
Total	1,724.2				1,832.9	-108.7
Ave.		27.0	29.2	24.9		

R = Rainfall
E-T = Potential Evapotranspiration
SR = Surplus Rainfall

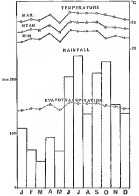

Figure 1.--Temperature and rainfall at Belize City.

permanently wet. Palmetto palm clumps (Thrinax argentea Lodd and Thrinax wendlandiana Beccari) also occur especially on flat land near the coast.

The present vegetation does not change greatly over the area which includes the Pine Ridge soils. This is in large part due to the almost uniform low soil fertility and the frequency of grass fires. The present trees and grass species are those which are best able to withstand fire.

Geology

Existing geological data give evidence that the Puletan soils were formed on an old coastal deposit. Much of the parent material came from the Maya Mountains. In fact, the greater part of the soils of British Honduras are directly or indirectly derived from the Maya Mountain rocks.

The Maya Mountains are formed chiefly from hard and very ancient rocks (Paleozoic). These are both arenaceous and argillaceous in texture and belong to two separate cycles of sedimentation. Molten rock was intruded beneath and between these sediments and on cooling gave rise to granite and phorphyrite. Subsequently some of the sediments became cemented by silica and the very hard rock quartzite was formed. Consequently, the main mass of the Maya Mountains is made up of quartz-rich rocks with few minerals which contain plant nutrients. There are no P deposits of any size and no basic or intermediate volcanic rocks containing K, Mg, Ca, S, or micronutrients. There are also no deposits of volcanic ash, despite the relatively close proximity of active volcanoes in

Guatemala (250 km to the SW). Therefore, soil parent materials derived from the Maya Mountains have a poor reserve of most of the nutrients required for normal plant growth. In terms of natural soil fertility, it may be concluded that the contribution of the inorganic cycle is small. The organic cycle contains a small reserve of plant nutrients, but the size of its contribution is subject to the length of time in which the plant cover remains undisturbed. When the organic matter is destroyed by fire the loss of soil fertility is considerable.

Wright *et al.* (159) stated that the weathering products of the Puletan soil parent material are quartz sand and clay. DTA and X-ray analyses of these soils indicate that the clay fraction less than 2 microns is predominatly kaolinitic. It contains much 7.4Å metahalloysite and a little 11.08Å hydrated halloysite, but also a considerable amount of 18.8-22.2Å montmorillonite.

One important problem of the Puletan soils pointed out by several investigators (34, 60, 159) is erosion by lateral movement of water. This is a consequence of frequent intense rain showers and an almost impervious, clay subsoil. Thus, quite often during the rainy season, a sheet of water several cm thick accumulates on the soil surface. The very gently sloping topography of these soils makes runoff very slow, but soil separates are transported downhill where they are deposited.

Soil Phosphorus

The literature covering practically all the phases of soil P is enormous. Nevertheless, the study of soil P is still a topic of major importance, not only because P is one of the major essential plant nutrients, but also because (1) it is present in the soil in relatively small quantities, 0.022 to 0.083% P out of the total P content of 0.12% P in the lithosphere (outer crust of the earth) and (2) it tends to react with soil components to form relatively insoluble compounds of slow availability to plants.

Forms of Soil Phosphorus

It is stated in text books (80, 124, 138) that P in soils is found in organic and inorganic forms and that the relative proportion of the P in these two categories varies widely. Organic P tends to increase or decrease in direct relationship with the organic matter content, hence, it is comparatively low in subsoils and higher in surface soils. Patel and Mehta (110) indicated that organic P in surface soils ranged from as low as 0.3% to as high as 95% of the total P. Usually organic P occurs in the form of phospholipids, nucleic acids, and inositol phosphates. The inorganic fraction occurs in numerous combinations with Fe, Al, Ca, F, and other elements. These compounds are only slightly soluble in water. The content of inorganic P in soils is almost always larger than the organic fraction.

Hemwall (66) reported that fertilizer P recovery by a crop planted immediately after fertilization amounts to only 10 to 30% of that applied. The remaining 70 to 90% is either precipitated by soluble cations present in the soil solution, sorbed by the soil complex, or finally immobilized by the soil microorganisms. It is now evident that the role played by soil microorganisms is relatively minor and that chemical precipitation and physicochemical absorption play the major roles. Therefore, the process by which soil P is rendered insoluble and slowly available to plants, "fixation" or "retention", is of considerable importance in plant nutrition.

Phosphorus Fixation

The process of P fixation was recognized as early as 1850 when Way (151) poured water solutions of sodium phosphate and guano in dilute sulfuric acid over a layer of calcareous soil. All of the P was retained by the soil which suggested that an insoluble calcium phosphate was formed.

Since that time, the literature concerning P fixation has become voluminous and has been critically reviewed by Midgley (93), Wild (157), Dean (42), and Hemwall (66). The two most accepted theories for P fixation are adsorption and chemical precipitation.

The investigators who support the adsorption theory (19, 85, 90, 99, 128) have tried to show that fixed P is in an exchangeable form and that it can be replaced by other anions. Hydroxyl ions (128, 135) are quite effective in replacing or liberating adsorbed P, but in some instances it is likely that the fixing complex was partly dissolved due to increased alkalinity.

Citrate, oxalate, silicate, and fluoride ions are also reported to be capable of displacing phosphate ions which are fixed by soils (41, 44, 135, 141). Most of the scientists supporting this theory have worked with purified colloids or specially prepared soils and used water as the extracting medium, therefore, the importance of such fixation under actual field conditions is not well established.

According to the chemical precipitation theory, phosphates may be chemically fixed by precipitation with soil bases under acid or alkaline conditions. Several investigators (20, 76, 140) considered that Fe and Al oxides and hydroxides are the main agents of P fixation in acid soils. Iron and Al phosphates are slowly soluble and difficultly available to plants.

In a generalized manner P fixation in acid soils has been visualized as follows (42):

$$\underset{\text{clay minerals and exchange sites}}{M_2O_3H(OH)_3} \rightleftharpoons (M(H_2O)_x^{+3}A_y^{to\ +1} + A + H_2PO_4^- \rightleftharpoons \underset{\text{precipitated or adsorbed}}{(M(H_2O)_xA_2H_2PO_4}$$

where M = cations of Fe or Al
A = oxide or hydroxide

Iron and Al are found concentrated in the clay fraction of most soils. They occur in the clay minerals in octahedral linkage, Al is found also in tetrahedral linkage. They can occur as free oxides and hydroxides such as gibbsite $Al_2O_3 \cdot 3H_2O$ (4), hematite Fe_2O_3, goethite and limonite $2Fe_2O_3 \cdot 3H_2O$, and magnetite Fe_3O_4 (29). Except in acid soils, the amount of Fe and Al in the soil solution is small.

Various scientists working with hydrogels (86, 99), ferric hydroxide (74), and soluble Fe and Al (86, 99) have concluded that the formation of Fe and Al phosphates in soil is a result of P fixation based on the following evidence:

1) Correlations have been established between P sorption and the amounts of Fe and Al in soils.

Phosphate sorption has been shown to very inversely as the $SiO_2:(Fe_2O_3+Al_2O_3)$ ratio of soil colloids (127, 141). Gile (56) found in a pot experiment that the efficiency of superphosphate decreased as the SiO_2 $(Fe_2O_3+Al_2O_3)$ ratio of the soil colloid decreased. Metzger (89) found a significant correlation between total Al_2O_3, Fe_2O_3, $(Al_2O_3+Fe_2O_3)$ and phosphate sorption in 42 samples. He also found that the reduction in phosphate sorption capacity, due to extraction with .002 N sulfuric acid, when expressed as a percentage of the original sorption capacity was correlated with the amount of Fe that was soluble in the extracting reagent. He established a correlation between the percentage of total Fe_2O_3 that dissolved in 0.002 N sulfuric acid and the percentage reduction in the phosphate sorption capacity that resulted from acid extraction. A similar correlation was not found with Al.

2) Iron and Al have been removed from soils and soil colloids and the effect on phosphate sorption has been studied.

Toth (140) and Kelly and Midgley (74) used the hydrogen sulphide method of Drosdoff and Truog (46) to show that the removal of Fe and Al oxides from soil colloids reduced P fixation. Similar results have been reported by several other investigators (12, 30, 35) after removal of the Fe and Al by a slightly modified hydrogen sulphide method.

3) Iron and Al compounds have been added to soils and soil colloids and the effect of P fixation has been studied. Wolkoff (158) found that the addition of ferric chloride to a soil treated with rock phosphate reduced the amount of phosphate dissolved by 0.2 N nitric acid. Aluminum chloride had no effect. Doughty (45) saturated a peat soil with Fe and Al ions by leaching with solutions of ferric chloride and aluminum chloride. He found that both the Fe and Al caused a considerable increase in P fixation.

4) Compounds formed during P fixation have been identified by comparing the effect of pH on the solubility of Fe and Al phosphates. Teakle (137) found that precipitation of phosphate was greatest with

Fe at pH 3 and with Al at pH 6.8. McGeorge and Breazeale (87) and Stelly and Pierre (133) reported results of the effect of pH on the solubility of Fe and Al phosphate minerals. Stelly and Pierre found that the lowest solubility of the aluminum phosphate minerals wavellite and variscite was in the pH range 4.5 to 7.0 and of the Fe phosphate minerals vivianite and dufrenite in the pH ranges 3.0 to 7.0 and pH 3.0 to 6.0, respectively.

Doughty (45) studied the retention of phosphate by a peat soil over the pH range 3 to 10. He attributed P retention at low pH values to Fe and Al. Scarseth (128) found that the greatest retention of P by an electrodyalized bentonite titrated with sodium hydroxide was at pH 6 to 7. He thought this was due to a reaction of the phosphate with the Al of the clay mineral. Black (12), working with Cecil clay, found a maximum in the phosphate sorption curve at pH 3 to 4, which he thought was due to hydrous iron oxide. He found that the amount of P that was retained at this maximum was reduced by the removal of the free iron oxide. He also concluded that the maximum in the phosphate sorption curve at pH 6 to 7, which he found with a sample of kaolinite, was due to absorption by free aluminum hydroxide. The Al was thought to solubilize slowly, especially under more acid conditions, because after 30 days' shaking, the maximum had shifted to pH 5 to 6.

The concentration of P in the soil solution in alkaline or calcareous soils appears to be governed by three different mechanisms

1) Precipitation as dicalcium-phosphate.

An increase in the soil pH favors the formation of diphosphate ions. In addition the solubility of the Ca orthophosphates decreases in the order mono, di, and tricalcium phosphate. In most alkaline soils the activity of Ca is high. This coupled with a high pH favors the precipitation of relatively insoluble dicalcium phosphate and other basic Ca phosphates such as hydroxy-apatite and carbonate-apatite.

Way (151) and Voelcker (148) supposed that an insoluble Ca phosphate is formed when a soluble phosphate is mixed with soil containing calcium carbonate. This insoluble P was assumed to be either dicalcium phosphate or tricalcium phosphate, though the latter was thought to be produced in all soils containing more than a trace of calcium carbonate.

McGeorge and Breazeale (86) later postulated the formation of carbonate-apatite in soils containing a high percentage of calcium carbonate. Dean (40) fractionated the P contained in the slightly calcareous soil at Rothamsted and concluded that P applied as superphosphate was retained as tricalcium phosphate or apatite. MacIntire and Hatcher (81) also made the suggestion that fluorapatite was formed in calcareous soils.

MacIntire and Shaw (82) showed that dicalcium phosphate mixed with calcium carbonate and distilled water and kept under laboratory conditions undergoes slow transformation to tricalcium phosphate. Thirty percent of the dicalcium phosphate was converted to the tricalcium form in the first week, but after 12 months 40% of the dicalcium phosphate remained unchanged. They also suggested that the dicalcium phosphate probably persists in moderately limed soils for a considerable period.

2) Precipitation of phosphate ions on the surface of calcium carbonate particles.

This occurs in soils that contain free calcium carbonate. The end product of the reaction seems to be a relatively insoluble salt of Ca, P, and perhaps $CO_3^=$ or OH^-.

3) Retention of phosphates by clays saturated with Ca.

These clays are capable of retaining greater amounts of P than those saturated with Na or other monovalent ion. A linkage such as clay-Ca-H_2PO_4 has been suggested.

Pratt and Thorne (115) showed that Ca-saturated clays fix far more P in the alkaline range than Na-saturated clays, and that the Ca clay fixes more P as the pH is increased as would be expected from the decreasing solubility of Ca phosphates with increasing pH.

Another interesting aspect of P fixation in soil is the form that applied P generally assumes. Cheng and Jackson (32) stated that the distribution of soil inorganic P measures the degree of chemical weathering, the chemical weathering sequence is Ca-phosphate ⟶ Al-phosphate ⟶ Fe-phosphate and finally occluded phosphate. In two latosols they found Ca-phosphate (1%), Al-phosphate (0-3%), Fe-phosphate (10-13%), and occluded phosphate (66-78%). They concluded that the distribution of various forms of inorganic P in the soil is controlled by the activities of the various ions which reflect soil pH, age, drainage, and mineralogical nature.

Cheng and Chu (33) found that soluble P added to six soils, with pH values ranging from 5.3 to 7.5, and kept at field moisture capacity for three days was mainly fixed as Al-P followed by Fe- and Ca-P. In two latosols the amount of Fe-P surpassed that of Al-P. After 100 days of flooding, Fe-P became the dominant form in all six soils. With time, Al and Ca-P gradually changed to the less soluble Fe-P, the rate of transformation increasing with the moisture content of the soil.

Manning and Salomon (83) working with a silt loam soil at the Rhode Island Experiment Station found that after 65 years of P fertilization, superphosphate increased the Al-P fraction most with smaller increases for Fe-P and Ca-P. The organic P fraction was not greatly affected by various levels and sources of applied P. Hortenstine (69) investigated the effect of lime and P fertilization in Lakeland fine sand. He obtained significant increases in water soluble-P, Al-P, Ca-P, and total P. The largest increase was in the Al-P fraction.

Fiskell and Spencer (48) investigated a Lakeland fine sand where 25 tons of lime and 13,440 kg of P/ha were applied to citrus over a 6-year period. They found that P forms were Al-P > Fe-P > Ca-P. Robertson and Hutton (119) studying the retention of fertilizer elements in a Red Bay fine sandy loam found an increase in the Al-P fraction from 30 to 414 kg/ha in a period of 7 years. The Fe-P fraction increased from 69 to 274.4 kg/ha.

Yuan et al. (160) investigated three different Florida soils, Red Bay fine sandy loam, Leon fine sand, and Norfolk loamy fine sand. They found that after treating the soils with six P levels and then separating the various forms of P by the fractionation method of Chang and Jackson (31) over 80% was retained as Al-P and Fe-P. Less than 10% was in the water soluble and Ca-P forms. The ratio of Al-P to Fe-P increased with the rates of applied P for the three soils. This was more evident for Red Bay fine sandy loam and Norfolk loamy fine sand than for Leon fine sand.

Robertson *et al.* (118) working with Red Bay fine sandy loam and Norfolk loamy fine sand which are high in Al and Fe found that after two years, 246.4 kg/ha of P from concentrated superphosphate applied to the first soil raised the total P 106.4 kg/ha of which 60.5, 31.0, and 5.6 kg/ha were present as Al-, Fe-, and Ca-P, respectively.

Hortenstine (70) investigated Lakeland sand and Leon fine sand from Florida, and Puleton loamy fine sand from British Honduras. He reported that liming these soils at rates of 0, 2,240, 4,480, and 6,720, kg/ha resulted in linear increases in P fixation. Most of the adsorbed P was present as Al-P in each of the soils.

Liming and Phosphorus Availability

Liming soils reduces soil acidity and supplies Ca or Ca and Mg to plants. Albrecht and Klemme (3) reported that application of limestone and superphosphate to mineral soils approximately doubled the P content of lespedeza forage over that contained in plants from soils receiving superphosphate alone. Data by Davis and Brewer (39) indicated that liming soils low in Ca enabled corn and oat crops to utilize larger quantities of P supplied by superphosphate.

Sewell and Latshaw (129) found that increasing quantities of lime increased the P content of the first and second cuttings of alfalfa grown on an acid mineral soil to which superphosphate was added. Lime alone had little effect on P absorption. Lawton and Davis (78) studied the effect of liming two strongly acid Rifle peat soils on the growth and absorption of soil and fertilizer P by field beans, sudangrass, and corn under greenhouse conditions. They found that the dry weight of field beans was markedly increased by applying up to 12 tons of calcium carbonate per acre. The growth of corn was depressed when more than 3 tons per acre was applied. Liming had little or no effect on the yield of sudangrass. Plant P concentrations were depressed by successive applications of calcium carbonate, this was probably due to a decrease in the proportion of $H_2PO_4^-$ ions in the soil solution.

Robertson *et al.* (118), working with Florida soils in pot tests, found that liming soils relatively low in residual P increased the availability of applied P to pH 6 to 6.5 when the sesquioxide contents of the soils were high, but had no effect where the sesquioxides were low. Liming these soils above pH 6 or 6.5 caused the percentage of P in the plant from the fertilizer to level off or decline. He speculated that this was due to the formation of relatively unavailable tricalcium phosphate. Liming soils high in residual P reduced the availability of fertilizer P regardless of the sesquioxide content. Uptake of P from currently applied superphosphate was highest from the soils high in sesquioxide content irrespective of rate of liming.

Peech (111) also found that the correction of excessive acidity of sandy Florida soils by liming not only assured adequate supplies of available Ca and Mg but also reduced leaching of cations and thus tended to conserve the more valuable fertilizer constituents. He found that increasing the application of lime caused an increase in the amount of readily available P as determined by Truog's method.

Davis and Brewer (39) grew Austrian winter peas (*Pisum arvense*) and common vetch (*Vicia sativa*) with various fertilizer treatments at a number of locations on upland soils of Louisiana. The results showed that liming soils low in Ca enabled the crops to utilize larger quantities of the P supplied by superphosphate. Lime alone produced an increase in Ca concentration only, but lime plus superphosphate resulted in increased Ca, P, and N concentrations.

Liming acid soils to increase the availability of P to plants has become a common practice in the humid regions of the temperate zones. The soils in the tropics have not been studied as closely as temperate soils, and knowledge of the effects of lime on tropical soils is still limited and controversial.

Vanmaa (146) stated that the connection between the pH and Ca status of temperate zone soils is frequently absent in sub-tropical and tropical soils and, therefore, the dominant role of Ca in soils of temperate climate is taken over by other cations in soils of the tropics, especially by Al. Consequently in tropical soils the normal correlation between pH value, Ca status, and lime requirement vanishes.

In recent years the problem of liming acid soils of the tropics has received some attention. Hardy (62) working with sugar cane soils in Guyana found the effect of liming was highly beneficial. Awan (8), in field experiments conducted at El Zamorano, Honduras, reported that highly significant yield increases were obtained when an acid soil (pH 5.5) was limed to pH 6.5. The highest yields were obtained on plots receiving both lime and P. Corn, sorghum, beans, and cowpeas were the crops recorded. Fox et al. (49) in Hawaii stated that the fixation of P is so critical in many tropical soils that high rates of P fertilizers are required for adequate plant nutrition. A tempting solution to the problem is the assumption that P availability to plants increases as soils are limed to pH 7. However, this generalization may not apply in the tropics.

Russell and Richards (122) reported that in the tropics and subtropics, liming only improves crop yields on very acid soils and usually reduces yields on moderately acid soils.

Chemical Soil Tests for Available Phosphorus

Many methods of measuring available P have been proposed as the basis for fertilizer recommendations. Such determinations in any one group of soils by different methods, however, frequently results in conclusions that differ with respect to the P status of the soils concerned. Therefore, the selection of the appropriate method for measuring soil P is not always easy.

In general, the soil P available to plants may be evaluated by using an extractant that will remove P related to that available to plants. In order to make these studies, it is necessary to correlate the P removed by a particular extractant with yield data over a period of time.

Various extractants such as inorganic acids, organic acids, pure or carbonated water, dilute alkali solutions, and buffered salt solutions have been proposed for these studies. Sulfuric acid has been used by a number of investigators (10, 142). Bray and his associates (21, 22, 23) developed extracting solutions that include the fluoride ion for replacement of adsorbed P from the anion exchange complex of the soil. Olsen et al. (104) advocated the use of 0.5 *N* sodium bicarbonate at pH 8.5, which they claimed to be well suited for predicting the available P status on both acid and alkaline soils. Saunder (126) has suggested the use of a drastic reagent, hot 0.1 *N* caustic soda, for determination of available P in tropical soils.

The National Soil and Fertilizer Research Committee on Soil Testing (100) compared a number of chemical tests involving 74 soils which varied widely, but whose P requirements were known. It was found that the chemical tests agreed better with greenhouse tests than with field trials. Weak extractants such as H_2O and CO_2-H_2O were more suitable for alkaline soils than for acid soils, and strong acid extractants were more satisfactory for testing acid soils.

Franklin and Reisenauer (50) compared NaOAc, $NaHCO_3$, and Bray methods 1 and 2 (0.03 $\underline{N}$ NH_4F + 0.025 $\underline{N}$ HCl and 0.03 $\underline{N}$ NH_4F + 0.1 $\underline{N}$ HCl) with 17 Washington soils. Both the NaOAc and $NaHCO_3$ extractants proved to be satisfactory, but the latter correlated better with plant response. In New Mexico, Pock and Gomez (109) tested the relative merits of $NaHCO_3$, $CO_2 - H_2O$, H_2O, and Bray methods on soils that were usually planted with cotton or alfalfa, and concluded that water-soluble P gave the best measure of available P.

Robertson and Hutton (117) made an evaluation of various chemical extractants as a quantitative measure of available P. Correlations were made on 9 Florida soils with corn as the indicator plant. The chemical methods used were Bray 1, Bray 2, and Truog. Results showed that the Truog method most nearly characterized the available P in soils with low P fixing capacity. For the soils with high P fixing capacity, the Truog method was satisfactory on virgin soil, but when residual P was present it did not remove sufficient P. When the residual P was in the order of 56 kg P_2O_5/ha, Bray 1 extractant (0.03 $\underline{N}$ NH_4F + 0.025 $\underline{N}$ HCl) was satisfactory. When the residual P was over 224 kg P_2O_5/ha, Bray 2 (0.03 $\underline{N}$ NH_4F + 0.1 $\underline{N}$ HCl) gave a better measure of the available P.

Smith and Cook (131) made a comparison between Bray 1 and 2 methods and Spurway's method (0.018 N acetic acid) with 14 different soils of Michigan. Both of Bray's methods provided a considerably clearer picture of P availability because the fluoride in the extracting solution removed the adsorbed P. An extracting ratio of 1 part of soil to 50 parts of extracting solution gave better results than the 1 to 10 ratio.

Salomon and Smith (125) studied a silt loam soil of moderate acidity which had received P from several sources for 48 years followed by 10 years without additional P. Available P was determined by several methods including Bray 1 and 2, Truog, Peech, Thornton, Morgan, Olsen, and sodium acetate pH 5.7 + NaOH 0.1 M. The Peech and Truog methods gave the best indication of probable crop response to P.

Weir (153) estimated the available P of 12 soils in Jamaica, with various chemical methods. He found that the 0.002 N sulfuric acid method by Truog was the best indicator followed in decreasing order by the 0.03 N NH_4F + 0.1 N HCl method of Bray; the 0.5 M sodium bicarbonate method of Olsen; the 10% sodium acetate method of Morgan, and the 0.1 N sodium hydroxide method of Saunder.

Chang and Chu (33) classified 26 soil samples into 3 groups according to their P distribution patterns, namely, (1) soils dominating in Fe-P (2) soils dominating in Fe and Ca-P,and (3) soils dominating in Ca-P. Available P was determined by Olsen, Peech, Bray 1, Bray 2, Bray 4 (0.5N NH_4F+0.1N HCl),Truog, and North Carolina methods. Values for available P in the first group of soils were all highly correlated. For the second group of soils, Olsen, Peech and Bray 4, North Carolina, Truog, and Bray 1 and 2, respectively, were highly correlated. For the third group of soils, the Bray 2, Bray 4, North Carolina, and Truog methods were highly correlated. The high correlation coefficients were explained by the similarity in the selectivity of dissolution of inorganic phosphates in the extractants used.

Bingham (11) made an interesting and useful survey of methods currently in use for measurement of available soil P in the U.S.A. He established limits of adequacy (low, medium, and high) for each method for the states in which the methods were used. Thus, for acetate solution extractants (New England, Florida, Mississippi, Texas, and Alaska) values less than 5 to 10 ppm P were low for most crops. For HCl-H_2SO_4 extractant solutions introduced by North Carolina, 10 ppm P or less indicated a deficiency. For the Bray methods (central and midwestern states) 10 ppm P or less was low.

Baker and Hall (9) compared various extractants which might be superior to the Morgan method for predicting the P status of soils in Pennsylvania. With respect to the amount of P removed from soils, the extractants ranked in the order Purdue, Bray 1, Morgan, Experimental, and $CaCl_2$. The test values obtained by one method were not closely related to values obtained by other methods for these soils. The Bray 1 method was most accurate for predicting plant uptake of P while the Purdue method was least accurate. (Note:) Purdue method. (0.075 $\underline{N}$ $Na_2C_2O_4$ + 0.255 $\underline{N}$ NaOH). Experimental method. (0.002 $\underline{N}$ HCl + 0.002 $\underline{N}$ NH_4F). $CaCl_2$ method: $CaCl_2$ 0.01 $\underline{M}$.

Mobility of Phosphorus in Sandy Soils

The nutrient elements contained in fertilizers added to the soil may be washed away by surface runoff, leached from the soil, lost in a gaseous form, or retained in the soil. Those elements held in the soil may remain soluble and easily available to plants or may become difficultly soluble and only slowly available.

When P fertilizers are applied to the soil, P is commonly retained with the result that it remains in that part of the soil profile in which it has been placed. Invariably this has been true in loams and clays, and since these comprise a large part of the arable lands, the concept of immobility of soil phosphates has been taken largely for granted.

Two of the soil factors that determine to a large extent the efficiency of fertilizers are fixation of ions into nonexchangeable and difficultly available forms. Fixation presents a serious problem in fine textured soils, but on the other hand, leaching of soluble fertilizer constituents constitutes an equally important factor governing the utilization of ions in sandy soils of low natural fertility. Therefore, when dealing with sandy soils, it appears that solubility of fertilizer materials is not necessarily a good criterion of fertilizer availability.

Ozanne et al. (107) showed that P from superphosphate may leach from sandy soils instead of being firmly bound in the surface layers as occurs with fine textured soils. It was then suspected that P fixation in loams and clays might take place by a different mechanism than in sands. A series of virgin soils, including some sands, was tested for their capacity to fix phosphate. It was found that their fixation capacities were accounted for by their content of Al and Fe. Thus, this relationship appears to be the same for sands as for loams and clays although the latter soils have a far higher fixation capacity.

Ozanne (108) used ^{32}P in a soil of deep siliceous sand of pH 5 with 5.3% organic matter in the 0 to 10 cm layer and showed that the distribution of radio-P fixed down the profile followed a trend similar to the distribution of organic matter, suggesting that organic matter strongly influences P fixation. He also found that the correlation coefficient between P fixed and organic matter content was r=0.96. These additional results gave evidence that an increase in organic matter content of a sandy soil may increase not only its CEC but also its ability to retain P. He concluded by stating that apparently the nutritional problems presented by sandy soils differ only quantitatively rather than qualitatively from those of other soils.

Ozanne et al. (107) measured leaching losses of P in 7 field trials, on loamy sand soils, where P was broadcast as superphosphate. Losses from the 0 to 10 cm surface soil ranged from 17 to 81% of the applied P. Lime applications at the rates of 440 and 1,680 kg/ha increased P retention from 11 to 16% at the highest rate.

The relationship presented by Ozanne et al. (107) between native P content of the soil and its capacity to retain applied P is of interest. Soils having large native P contents may be capable of retaining large quantities of applied P fertilizer. The following are analytical data presented by several investigators.

Reference	Native P ppm	Applied P loss%	O.M. %
Neller (1946)	27	90	3.0
Neller *et al.* (1951)	80	85	3.2
Hingston (1959)	20	71	2.6
Doak (1942)	420	23	10.2
Walker *et al.* (1959)	470	20	18.0
Saunders (1959)	2,300	nil	20.0

According to these data, soils containing less than 100 ppm native P and less than about 6% organic matter are liable to lose considerable quantities of fertilizer P. These critical levels should be expected to vary with soil type, climate, and management practices. In the data presented, the first three soils having less than 100 ppm native P and less than 6% organic matter showed great losses of applied P. The intermediate soils, having less than 400 to 500 ppm native P and between 10 and 18% organic matter showed small losses of applied P, while the last soil with 2,300 ppm native P and approximately 20% organic matter lost no applied P.

Numerous investigators have studied the movement of P fertilizers in sandy soils of Florida, U.S.A. Neller (101) conducted some lysimeter experiments to study leaching losses of P fertilizer from a Leon fine sand. The 0 to 20 cm layer of soil was placed in a series of 4-gallon lysimeters. Various carriers of P were mixed in the surface 10 cm and leachings from rainfall were collected for a period of about 5 months. Results showed that 79.1% of the P from ordinary superphosphate was leached from unlimed sandy loam soil. From rock phosphate, 40.8% P was leached from unlimed soil and 8.9% P from limed soil. In sandy loam soils, P recovery in the leaching ranged from traces to 1.6%. Neller (103) working with Leon, Immokalee, and Rutledge fine sands found that fertilizer P leached from these fine sands, but that leaching was largely eliminated by liming. In contrast, some soils of western Florida such as Dunbar and Marlboro fine sandy loams, showed a high fixation of P. Neller et al. (102) investigated Leon and Immokalee fine sands and found that 1 to 2 tons of lime applied per acre reduced the loss of fertilizer P from the root zone considerably. When soil pH was as low as 4.5, practically all of the P of superphosphate leached from the surface 7.5 cm in about a year.

Spencer (132) working with soils from the Citrus Experiment Station at Lake Alfred, Florida, indicated that essentially all of the added P was retained within the citrus root feeding zone, even though it may have been leached from the surface 15 cm of soil. The greatest accumulation occurred within the 30 to 90 cm zone, though some P had leached to a depth of 2 m.

Hortenstine (70) reported that liming resulted in linear increases in P-fixation capacity of three soils studied under laboratory conditions, namely Pulaten loamy fine sand, Lakeland sand, and Leon fine sand.

Experimental work on the fate of fertilizers added to the soil has been performed with lysimeters in the open under natural or artificial rainfall, with soil columns in the laboratory, and with undisturbed profiles in the field. Recently radioactive isotopes of P and Ca were used to trace the movement of these nutrients in the soil and also to trace the uptake by plants.

Fraps (51) placed soils in tubes 5 cm in diameter and 35 cm long, mixed 1 g of superphosphate with the top 7.5 cm of soil, added 100 ml water, and allowed the column to stand 24 hr. Then water was percolated through the column until 1 liter was collected. With soils having a high fixing capacity, almost no P was found in the percolate. Later several refinements of this basic procedure were used in studying the effect of fixation and fertilizer properties on the penetration of P.

Larsen and Warren (77) made studies on the leaching of ^{32}P in 5 organic soils and 1 mineral soil. Phosphorus retention appeared closely related to the sesquioxide content of the soil and its apparent degree of decomposition. Havord (65) in Trinidad investigated in the laboratory leaching losses and residual amounts of nutrient elements, particularly N, P, and K from fertilizers added to columns of soil.

Midgley (91) in Wisconsin studied movement of P in soils with special reference to pasture fertilization, both in the field and under controlled laboratory conditions. Results indicated that little or no penetration took place with heavy soils, and he speculated that with coarse textured soils appreciable movement may be expected.

Stephenson and Chapman (134) studied the extent to which P penetrated into certain field soils which had received fertilizers for several years. They found little or no P penetration in very heavy soils regardless of the amount of P applied. In nearly all soils which received P fertilizer for several years there was a marked accumulation in the surface 15 to 30 cm.

Plant Chemical Composition as an Index of Soil Fertility

Yield data as determined by field or pot-tests have been the most widely accepted criteria for evaluating fertilizer responses, while plant analyses have also received considerable emphasis since plant composition is effected by the nutrient content of the growing medium. A more thorough knowledge of optimum nutrient requirements for plants may be obtained by a combined study of these criteria. Thus, plant analyses at the maximum yield should show the nutrient requirements of such critical elements as Ca, P, and K from which more efficient fertilizer recommendations could be obtained.

Numerous factors often operate simultaneously to change the chemical composition of crops and, therefore, it is extremely difficult to evaluate correctly the part played by any one factor. In certain cases, the application of one nutrient element may create severe unbalanced plant nutrient conditions in the soil and consequently in the chemical composition of the crop. In other cases, where one or more nutrients are supplied by means of fertilizers, the result may be increased uptake of several other essential plant nutrients.

Effect of Soil Properties on Plant Composition

Studies dealing with the relationship between soil properties and plant composition are relatively scarce. The widespread use of fertilizers to correct plant nutrient deficiencies in the soil and the difficulties encountered in making a proper evaluation of the influence of soil conditions on crop composition seem to be the main 2 factors responsible for the lack of more information on this subject. Most of the available literature found relates to grasses or cereal crops.

Much of the pasture grass is produced on unfertilized land and several investigators (6, 37, 52, 114) have observed that soils of a low fertility level generally produce grass and hay with a lower protein and P content than grass produced on fertile soils. Vandecaveye and Baker (143) found that grasses grown on organic soils contained smaller amounts of protein and P than grasses grown on mineral soils in the same localities. Fudge and Fraps (52) and Daniel and Harper (37) reported positive correlations between the N, P, and Ca concentrations of certain grasses and the available supply of these constituents in the soil.

Pugsley and McKibbin (116) noted that grasses produced on highly calcareous soils contained more Ca than the same species growing on other soils. Russell and Watson (123) at Rothamsted reported that soil properties have a definite effect on the N concentration in barley (*Hordeum vulgare*). When barley was grown in rotation with other crops, fine textured soils produced grain with high N, fine loam soils gave grain with medium N, and chalk soils and coarse loams produced grain with lowest N.

Willis and Harrington (156) working in Montana found that the P concentration of alfalfa (*Medicago sativa* L.) served as a means of detecting soil P deficiency. Low alfalfa P concentrations indicated low available P in the soil. Miller (94) noted that alfalfa grown on fine textured soils generally contained a higher percentage of P than alfalfa grown on coarse textured soils.

Stubblefield and DeTurk (136) in Illinois grew corn (*Zea mays*), oats (*Avena* spp.), and wheat (*Triticum vulgare*) on two different soils, one highly productive and the other of low productivity, and found that the low productivity of one of the soils was mainly due to poor drainage, and low available P and K.

Effects of Fertilizers on Plant Composition

Several investigators (5, 13, 26, 55) concerned with the effect of N fertilizers on the chemical composition of pasture grasses reported increased protein in pasture grasses as a result of N fertilization. Mortimer and Ahlgren (96) reported increases in protein and decreases in P and Ca concentrations in pasture grasses from applications of N fertilizers.

Olson and Dreier (105) reported that N fertilizers stimulated plant use of fertilizer P in a wide range of soil conditions. Ammonium apparently was more effective than nitrate in this capacity, especially during early growth stages. There seemed little doubt that a physiological function of N stimulated root activity in the uptake of fertilizer P. Grunes et al. (58), in a growth chamber experiment with barley growing on seven soils, found that the addition of N fertilizer generally increased total P absorbed by the plant from bands of concentrated superphosphate. Ammonium sulfate with the P band was more effective than separating the N and P bands. Indications were that the effect of N on P uptake was associated with increased top and root growth and also with decreased soil pH.

Negative effects of N fertilizer are also expected to occur. Murray et al. (98), Sautt and Hamilton (130), and Vandecaveye and Baker (143) reported that N fertilizers had no effect on or caused decreases in the amounts of protein in pasture grasses. These unfavorable results were attributed in certain cases to relatively small N applications. Large applications may result in unbalanced plant nutrient conditions which interfere with the normal functions of N in plant metabolism. In the latter case, fertilizers containing other deficient plant nutrients may be needed before satisfactory results can be obtained.

Brown (27) found that N fertilizers were not very effective in improving the quality of herbage on many Connecticut pasture lands unless they were supplemented with P. Moser (97) used Cecil sandy loam soil in a pot experiment and showed that Korean lespedeza (*Lespedeza stipulacea* Maxim) and Austrian winter peas made their optimum growth at pH 6 to 6.5. Plant analysis showed that Ca concentrations in both crops were influenced by the available soil Ca. Further Ca uptake resulted where double superphosphate applications were used while K in combination with superphosphate retarded Ca uptake.

Phosphorus and K fertilizers are also commonly applied to soils where pasture grasses are grown and if soils are acid in reaction, lime is usually applied as a supplement.

Brown (27) and Robinson and Pierre (120) reported definite increases in the P and protein concentrations in pasture grasses when various P fertilizers were applied to the soil. Davies and Chippindale (38), and Vinall and Wilkins (147) found larger P and Ca concentrations in pasture grasses produced on soils treated with P fertilizers either alone or with lime. Crampton and Finlayson (36) found that P and K fertilizers caused no significant changes in the composition of pasture grasses.

In general, it seems that N fertilizers applied to pasture lands are expected to result in an increased percentage of protein. Phosphorus fertilizer alone or with K also tends to increase P content or of both P and K and sometimes of P and Ca.

Part of the flora of the large majority of pasture and grass lands consists of clovers and other legume crops, which are capable of utilizing atmospheric N for their own growth, therefore, application of N fertilizers for the production of these crops as forages, provided they are properly inoculated, should not be of primary consideration.

However, Austin (7), Adams (1), and Adams et al. (2) reported that the N content of soybean hay was increased by the addition of N in complete fertilizer. On the other hand, Vandecaveye and Bond (144) reported that N fertilizer failed to exert any appreciable effect on alfalfa hay composition.

The fact that legumes contain large concentrations of mineral plant nutrients, suggests that their composition might be affected readily by P and K fertilizers applied alone or together, with or without liming of the soil. Grizzard (57), Sewell and Latshaw (125), and Blair and Prince (14) reported that P fertilizers alone or in combination with K fertilizers caused an increased percentage of P in alfalfa hay. Miller (94) found that sweet clover (Melilotus spp.) and red clover (Trifolium pratense L.) were more responsive to applications of P fertilizers than was alfalfa, because the P concentration in these crops in the hay stage of maturity was increased more uniformly by P treatment.

In general, it appears that although the results obtained with these fertilizers applied alone or together are variable, they produced an increased P concentration in the majority of legume hays.

Difficulties in making comparisons of the chemical analyses of herbage from different regions are often due to differences in stage of maturity at harvest, climatic conditions preceding sampling, and inclusion of more than one species in the sample. Most of the comparative analyses have been limited to N, P, and K. Calcium and Mg were frequently included but micronutrient analyses seldom were made. In the literature it is difficult, if not impossible, to find plant nutrient concentration standards indicative of critical levels for optimum plant growth. Some of these values are thus presented.

Kirk et al. (75) reported some data on the P concentration in pangolagrass (Digitaria decumbens Stent) grown on a Immokalee fine sand at the Ona Experimental Station, Florida, as follows (Table 2):

Table 2.—Phosphorus applied and herbage phosphorus content.

	P in Oven-dry Pangolagrass			
	Year			
Fertilization	1958	1959	1961	1963
	%			
0	0.10	0.08	0.05	0.06
Superphosphate	0.20	0.16	0.08	0.07
Superphosphate + lime	0.25	0.20	0.19	0.09
Rock phosphate	0.35	0.27	0.27	0.25
Triple superphosphate	0.23	0.15	0.10	0.08
Basic slag	0.23	0.18	0.16	0.14

Brown and Hollowell (28) reported comparative data for P and Ca concentrations in white clover (Trifolium repens L.) growing at different stations as follows (Table 3):

Table 3.--Calcium and phosphorus in white clover from various fertilized plots at several experiment stations.

Station	General fertilizer	Ca 1	P 1
		------- %	-------
Beltsville, Md.	N	1.26	0.50
	P	1.41	0.55
	K	1.33	0.50
Morgantown, W. Va.	P	1.62	0.29
	PL	1.92	0.29
Moorefield, W. Va.	None	1.43	0.30
	PL	1.53	0.32
Storrs, Conn.	P	1.44	0.34
	PL	1.57	0.39
	PLK	1.26	0.36
	PLKN	1.31	0.33

In general, white clover grown on heavily limed soil at Beltsville, Maryland, contained much less Ca, but much more P than in more acid soils of West Virginia and Connecticut. At Moorefield, West Virginia, the unfertilized clover contained as much P as clover fertilized and grown in poorer soil at Morgantown.

Gammon and Blue (53) reported on the K requirements of pastures grown on sandy soils in Florida, and the following data were obtained from several experiments with white clover and pangolagrass, and from a single experiment for the rest of the given crops (Table 4).

Table 4.--Potassium requirements for some pasture crops in Florida.

Plant	Minimum K for optimum growth (oven-dry herbage)	Maximum K in oven-dry herbage
	%	%
White Clover	2.0	5.0
Pangolagrass	2.0	4.9
Weeping Lovegrass	0.3	1.8
Pensacola Bahiagrass	0.6	3.0
Argentine Bahiagrass	0.9	3.4
Carpetgrass	0.75	3.4
Coastal Bermudagrass	1.0	3.1
Bermudagrass 99	0.8	3.0

Gammon (54) also reported that pangolagrass has a high K requirement for maintenance of maximum growth and gave the following table of minimum requirements for several grasses (Table 5).

Table 5.--Minimum potassium content required of pasture herbages for optimum growth rate

Pasture plant	K
	mg/g
White Clover	20
Pangolagrass	20
Coastal Bermudagrass	10
Argentine Bahiagrass	9
Bermudagrass 99	8
Carpetgrass	7
Pensacola Bahiagrass	6
Common Bahiagrass	5
Weeping Lovegrass	3

Hodges et al. (67) at the Range Cattle Experimental Station in Florida found that P concentrations in pangolagrass ranged from 0.25 to 0.30%. Hortenstine (69) studied the effect of 3 lime rates and

5 P rates on yield of oats grown on a Lakeland fine sand. He reported average P concentrations between 0.22% for a 28 lb/acre application and 0.28% for 125 lb/acre Calcium concentrations were 0.49% at the 55 lb/acre P application and 0.59% at the 111 lb/acre application. There was a linear increase in P uptake with increasing applied P. However, liming caused a linear decrease in Ca concentration of oat forage, and P fertilizer had no significant affect on Ca concentration.

Howard and Burdin (71) in Kenya, Africa, working on a mineral deficiency survey found that the average P content of 1,500 forage samples was 0.145%. Apparently the value of 0.14% is the minimum level of forage P required for normal animal growth. Average Ca concentration was 0.386% which was half the normal value for British pastures (0.72%). Average Cu content was 7.4 ppm, and a good pasture had above 5 ppm Cu. Average Mg content was 0.18% and average K was 1.95%.

Jardin (73) made a study of the chemical composition of forage plants from pastures in Central Brazil and reported that pangolagrass contained 0.23% Ca, 0.09% P, and 23 ppm Cu. Tergas[1] working with jaraguagrass in a hot dry savanna in Costa Rica reported N concentrations as high as 1.44% and P as high as 0.19%.

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[1] Tergas, L. E. 1968. The effect of nitrogen fertilization on the movement of nutrients from a tropical grass under soil moisture stress in a hot savanna. Ph.D. Thesis. University of Florida, Gainesville.

MATERIALS AND METHODS

Field Work

The selection of the area for investigation was primarily based on the soils map accompanying the report of the British Honduras survey team (159). In this report, the Coastal Alluvial Pine Ridge soils are described as comprising different types, as follows (Table 6).

Table 6.--Puletan soil textural types.

Set	Area ---ha---	Soil	Parent material
53	38,539	Puletan loamy sand	Coastal deposits
53a	17,460	Puletan shallow loamy sand and gravelly sand	Coastal deposits
53b	21,442	Puletan coarse sand	Coastal deposits
53c	36,721	Puletan sandy loam	Coastal deposits
53d	19,287	Puletan loamy coarse sand	Coastal deposits
53e	33,913	Puletan grey silty sandy loam	Coastal deposits and colluvium
53f	1,295	Puletan clay	Coastal deposits

According to the soils map mentioned above, the predominant soil in the Belize area is Puletan sandy loam, 53c. Consequently, this was the soil selected.

However, the soils map contained in the report of the survey team (159), which was in a scale 1:250,000, did not show all the different kinds of soils in the country. It was a reduction and a simplification of the information shown on a set of 8 sheets covering altogether about 21 m^2, these sheets, which were to a scale of 1:40,000, provided considerably more detailed information. According to this map, consulted at the Department of Agriculture in Belize City, the selected area of soils 53c actually comprised 2 different kinds of soil, which were identified as 53c-aP and 53c-aPs, thus described:

53c-aP Accumulating Puletan sandy loam

7.5 - 22.5 cm grey brown silty sandy loam

22.5 - 37.5 cm yellow sandy clay on yellow grey mottled sandy clay

Other features

Drainage: slow to poor

Ground water: seasonally at 15 - 37.5 cm

Vegetation: grass and sedge savanna

53c-aPs Accumulating Puletan loamy coarse sand

0 - 25 cm dull gray coarse loamy sand

25 - 37.5 cm mottled orange, gray brown, compact, clay sandy

Other features

Drainage: slow

Ground water: usually at 30 - 35 cm

Vegetation: savanna grass, sedges, and a few pines

In order to obtain representative soil samples of the area to be studied, two sites were selected, one in which soil 53c-aP was dominant and the other in which soil 53c-aPs prevailed.

To locate these sites, a reconnaissance survey was made with a screw auger 1 m long and 2.5 cm wide marked in 30 cm divisions. An average of 50 auger borirgs was made at each site. The exact location is indicated in Fig. 2 by Roman numerals.

Soil 53c-eP (Site I) was located 16 km west of Hattieville and 150 m north of the paved Belize-Hattieville-Cayo road. Soil 53c-ePs (Site II) was located 8 km from Hattieville and 120 m east of the paved Hattieville-Boom road.

One soil profile pit was dug at each of these locations. The dimensions of the pits were 1x1x1 m. Soil samples were taken from every pit, usually at depths where distinct changes in color, structure, texture, or consistency occurred. Notes were made on other features of each soil, in situ (Table 79). Four bag samples were taken at Site I and 5 at Site II.

Before sampling, the face of the pit was cleaned with a flat spade. The surface layer of litter, if any, and the superficial stolon-root-mat were carefully removed and discarded before applying a steel measuring tape for marking the sampling depths. Sampling was done by means of a truncated bricklayer's trowel sharpened at the cutting edge. A rectangular piece of beveled wood, about 45 x 30 cm was used to receive the soil slices cut vertically from each layer. The soil samples were transferred from the tray directly to polyethylene bags.

For determination of soil porosity, constant volume soil samples were obtained from the different layers in every pit by means of a brass cylinder with a volume of 68.7 cc. One of the ends was sharpened to allow easy penetration into the soil by hand pressure or by the

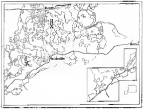

Figure 2.--Map showing location of Profiles I and II.

use of a rubber mallet. In all, 9 core samples were taken at Site I and 10 at Site II. They were placed in polyethylene bags and taken to Belize City for drying and shipment to the University of Florida. Wet weights were taken of all the core samples for calculation of pore space and water content. It should be pointed out that rain fell constantly during the whole period of soil sampling. No auger borings were attempted at the bottom of soil pits for identification of the soil below since water constantly trickled into the pit at the base and from the walls. Therefore, the full depth of soil examination was never more than 1 m. The profile descriptions are presented in the Appendix section.

After core and bag samples were taken at each of the sites, additional larger samples were taken for greenhouse investigations, as follows:

Site I	0 - 22.5 cm depth		Surface soil
	below 37.5 cm	"	Subsoil
Site II	0 - 15 cm	"	Surface soil
	below 30 cm	"	Subsoil

The zone between the sampled layers was considered transitional and was discarded.

These soil samples were bagged in cotton sacks, transported to Belize City and dried at the storage house provided by the Marketing Board of Belize.

In order to acquire more information, other samples comprising almost the whole set of the Puleston soils were collected, primarily for laboratory analysis. Approximately 18 kg of soil were taken at five different places at depths of 0-15 and 15-30 cm. Only Puleston coarse sand, 53b, was not sampled because this soil was inaccessible due to excessive rainy conditions.

In Belize City the soils were prepared for shipment to the University of Florida, core and bag samples were put in double polyethylene bags, other samples were put in double cotton and burlap sacks. A total of 3,182 kg (wet weight) of soil were air transported to Miami, Florida, distributed as follows:

Site I .	Surface soil	1,136 kg
	Subsoil	273 kg
Site II .	Surface soil	1,340 kg
	Subsoil	318 kg
Other Puletan soils		91 kg
Core and bag samples for laboratory analyses		27 kg

Soil samples were fumigated by the USDA Plant Quarantine Station on arrival in Miami, Florida, to conform with regulations. The soils were forwarded to Gainesville after fumigation.

Core samples were oven-dried at 105 C for 24 hr, cooled, and weighed for calculation of bulk density, pore space, and water content. Bag samples were air-dried, passed through a 2 mm sieve, bagged in polyethylene bags, and stored for chemical analysis. Soils for greenhouse investigations were also air-dried, passed through a 5 mm sieve, and stored in large polyethylene bags for further use.

Laboratory Investigations

Soil Physical Measurements

Determination of sand, silt, and clay contents was made by the standard Bouyoucos method (18) with 50 g of air-dried soil and the addition of 20 ml of dispersing solution (0.5 N sodium carbonate plus sodium silicate). Drastic agitation of the soil was applied for 30 min with a Hamilton Beach soil disperser. Distilled water was used to wash the contents of the cup into the special large cylinder and to make volume. The hydrometer reading for sand percentage was taken 40 sec after the contents of the cylinder had been thoroughly shaken by inverting the cylinder several times. A large rubber stopper was used to close the cylinder. The hydrometer reading for clay percentage was taken after an interval of 1 hr. Percentage of silt was obtained by subtracting the sum of the percentages of sand and clay from 100. Corrections for temperature were applied in every determination.

After the 1 hr reading, the suspension was washed onto a No. 300 sieve and materials that passed through the sieve were discarded. The portion retained on the sieve was dried at 105 C and shaken on a set of sieves consisting of one each of No. 18, 35, 60, 140, and 270 which rendered the very coarse, coarse, medium, fine, and very fine sand fractions, respectively.

Sticky point was determined by the hand-kneading process (59, 63). The value approximately coincides with the "field capacity" of a soil, which is usually measured by determining the moisture content when the soil has been saturated by rain and afterwards allowed to drain by gravity.

Index of texture determination is believed to furnish an approximate measure of the amount of moisture that can be held in the microreticulate structure of the colloidal components of the soil, that is, of capillary pore space, expressed as volume percentage. It involves two measurements, namely, sticky point moisture content (P) and sand content (S). With these values P and S, the index of texture was calculated from the following formula. Index of texture = P - 1/5 S (59).

Soil porosity is the percentage of the soil volume which is not occupied by solid matter. In a soil containing no moisture, the total pore space will be filled with air. The pores of a moist soil are filled with both air and water. The relative amounts of air and water present will depend largely upon the size of the pores. Most soil porosity determinations are based upon determinations of the bulk density of the soil at some arbitrary moisture content (15).

Undisturbed soil core samples were taken as previously explained. Bulk density was determined from the volume and weight of dried solid matter. True specific gravity, or particle density, was determined on oven-dried soil ground to pass an 80-mesh screen, with a 50 cc specific gravity bottle (16).

Finally total pore space (volume percent) was calculated from the formula:

$$\text{Total pore space} = \frac{\text{particle density} - \text{bulk density}}{\text{particle density}}$$

Capillary pore space volume was derived from the index of texture, thus,

Capillary pore space = index of texture x bulk density (59).

The non-capillary pore space was assessed by subtracting capillary pore space from total pore space.

The relative proportion of capillary to non-capillary pores furnishes a measure of soil structural properties. An ideal soil should have the pore space about equally divided between large and small pores. Such a soil should have sufficient aeration, permeability, and water-holding capacity to satisfy the requirements of most plants.

The porosity characteristics (total, capillary, and non-capillary pore space) were recorded as volume percentages. Determinations were made on each soil sample in duplicate. The total moisture content at the time of sampling was partitioned between capillary and non-capillary pore space. The difference between total pore space and the volume of water in the non-capillary pore space assesses the volume of air in the soil at the time of sampling. This, according to the literature (61, 64), should be at least 10% of the total soil volume for proper respiration of plant roots.

X-ray diffraction was used to identify clay minerals present in the clay fraction from the 0-15 and 37.5-90 cm horizons of Profile I and the 0-15 and 30-90 cm horizons of Profile II. Clay samples were prepared for analysis by the method described by Whitting (154). X-ray diffraction of Mg and K saturated samples was made by Cu radiation with Ni filter using a current of 10 ma.

Soil Chemical Measurements

Soil pH was determined potentiometrically with a Corning pH meter Model 7, containing a glass and a calomel reference electrode. The measurements were made in suspensions with distilled water and with 1N KCl, with a soil:liquid ratio of 1:2.5 in both instances.

Organic matter was determined by the wet combustion method of Walkley and Black (149).

Total N determination followed the standard macro-Kjeldahl method with 5 g of soil as described by Braland (24). The C/N ratio was calculated by assuming 75% oxidation of C.

Available P was determined by the Truog method with 0.002 N sulfuric acid as extractant solution. Phosphorus in the extract was determined colorimetrically by means of the Spectronic 20 at 650 mµ band (42, 72). Organic P determination was accomplished by the method outlined by Mehta *et al.* (88). Total P was determined by the perchloric acid digestion followed by colorimetric reading as described by Jackson (72).

Extraction of exchangeable cations was accomplished with a neutral solution of N ammonium acetate with 10 g of soil according to the method described by Peech *et al.* (112). The solution extracted was evaporated to dryness, the organic matter was oxidized with 6 N nitric acid solution and 30% hydrogen peroxide, and evaporated to dryness. The salts were taken up and diluted to 100 ml with 0.1 N hydrochloric acid. The adsorbed ammonia was leached with acidified sodium chloride solution (pH 3) to determine the total cation exchange capacity (CEC).

Exchangeable Ca and Mg in the extract were determined with the Model 303 Perkin-Elmer Atomic Absorption Spectrophotometer at wavelengths 4227, and 2852 Å (75).

Exchangeable K and Na in the extract were determined with a Beckman 2-Du Flame Spectrophotometer with Hydrogen-Oxygen burner assembly at 786 and 589 mµ wavelength (72).

Total Ca, Mg, K, Na, Fe, and Al were determined on a 0.1 g sample by decomposition with hydrofluoric acid according to the method described by Jackson (72).

Phosphorus Fixation and P Fractionation

The P fixation capacity of the Puletan soils was studied by the procedure described by Hortenstine (70). One or 5 g of soil were weighed into a 100 ml polyethylene centrifuge tube with 25 to 50 ml of a solution of known P concentration. The tubes were shaken for 4 hr and centrifuged. The supernatant liquid was analyzed for P. The P removed by the soil was considered to be fixed. The soil remaining in the centrifuge tube with 25 to 50 ml of a solution of known P concentration. The tubes were shaken for 4 hr and centrifuged. The supernatant liquid was analyzed for P. The P removed by the soil was considered to be fixed. The soil remaining in the centrifuge tube was successively extracted with 1$\underline{N}$ NH_4Cl, 0.5$\underline{N}$ NH_4F (pH 8.2), 0.1$\underline{N}$ NaOH, and 0.5$\underline{N}$ H_2SO_4 solutions to represent water soluble, Al-, Fe-, and Ca- phosphate, respectively, according to the method of Chang and Jackson (31).

The effects of lime on P fixation and in the distribution of P in its different inorganic fractions were also investigated.

Mobility of Phosphorus in Puletan Soils

Sulfur-absorption tubes 33 mm inside diameter and 20 cm long with fine sintered glass filters were used in these studies. Soil was placed in the tubes between two 1 cm glass wool pads. The glass wool pads lessened clogging of the filter and prevented compaction when water was added. Each soil column was suspended so that drainage could be collected in flasks without evaporation losses. Distilled water was poured into the tubes in increments of 50 ml to a total amount equivalent to the average rainfall registered in Belize City during the rainy period (June to January), namely, around 1,000 ml. Phosphorus in the leaching was analyzed after every addition of water had passed through the soil column. When P concentration in the leaching decreased noticeably, the amount of water was increased to 100 or 200 ml before P analysis. A Gast vacuum Model 0322-P2 was used to facilitate leaching of soils with high clay contents.

The following experiments were conducted.

Experiment 1

One hundred grams of topsoil with and without lime were put in the leaching tubes. Triple superphosphate, finely ground at rates of 60 and 120 ppm P, was thoroughly mixed with the top 10 g of soil. Leaching proceeded as explained earlier. Soils limed at rates of 0, 4,500, and 12,000 kg/ha were kept at constant moisture for about 30 days, then allowed to air-dry before use in the experiment. All treatments were in triplicate.

At the end of the experiment, the soil column was removed from the tubes by compressed air and divided into 3 portions. Each portion was dried separately at 105 C for 24 hr. The portions were cooled, weighed, and stored in polyethylene bags for analysis.

This experiment was repeated, except that after the P fertilizer was added to the soil, water was applied to just moisten the soil. The column was allowed to stand for 48 hr and then leached.

Experiment 2

It is of practical importance to find out how deep P fertilizer can move, or at what depths within the profile P retention occurs. A soil profile was simulated in leaching tubes by placing soil of the different horizons in successive layers as it occurred in the field. The arrangements were as follows.

Sandy soil

Depth of horizon (cm)	Depth in tube (cm)	Amount of soil (gm)
0-15	2	25
15-30	2	25
30-45	2	25
45-60	2	25
60-90	3	50
	Clay loam soil	
0-15	2	20
15-27.5	1.6	15
27.5-37.5	1.3	10
37.5-90	7	60

Lime at rates of 0, 4,500, and 12,000 kg/ha and P at 120 ppm was used. Each treatment was triplicated. Phosphorus fertilizer was thoroughly mixed with the surface soil (0-15 cm) which had been limed 30 days prior to the experiment.

Leaching, collection of leaching, and P analysis followed identical procedures used for previous experiments. When the profile contained soils of high clay content, suction was applied with a vacuum pump to speed up leaching. At the end of the experiment, the soil was removed from the tube, separated by horizons, dried at 105 C, and stored for analysis.

This experiment was repeated, except that the soil column was allowed to stand for 48 hr after P fertilizer was added to the topsoil and some water had been added to moisten the soil. The leaching process followed as for previous experiments.

Selected soil samples were analyzed for total P in each of the described experiments, in order to identify the depth at which P fixation occurred. It was calculated by the increase in total P concentration compared with control treatments. The fractionation method of Chang and Jackson was used to study the distribution of the retained P in the different inorganic fractions.

Available Soil Phosphorus and Crop Yield Study

Four chemical methods for available soil P were tested and results were correlated with pangolagrass yields from 3 consecutive cuttings, grown in the greenhouse. Two surface soils were used - Puletan sandy loam and clay loam. The methods were as follows:

1) One gram soil and 200 ml of $0.002\underline{N}$ sulfuric acid extractant buffered by addition of 3 g of ammonium sulfate to produce a pH of 3 in the final solution were placed in a 500 ml conical flask by the Truog's method. The suspension was shaken for one-half hour, filtered, and P in the filtrate was determined by the molybdophosphoric blue color method as described by Jackson (72).

2) Five grams of sandy soil or 2 g of clay loam soil were placed in a 100 ml centrifuged tube with 35 ml of $1\underline{N}$ ammonium acetate (pH 4.8). The suspension was shaken for 30 min and centrifuged (100). The supernatant solution was separated and used for P determination by the molybdophosphoric blue color method as described by Jackson (72).

3) Five grams of soil and 35 ml of Bray 1 solution ($0.03\underline{N}$ NH_4F + $0.025\underline{N}$ HCl) were placed in a 100 ml centrifuge tube, the suspension shaken for 1 min, and filtered (22). Phosphorus in the filtrate was determined by the molybdophosphoric blue color method as described by Jackson (72).

4) The Bray 2 procedure (22) was the same as for Bray 1, except that the extractant was $0.03\underline{N}$ NH_4F + $0.01\underline{N}$ HCl, and the suspension was shaken for 40 sec. Duplicate samples were extracted for each method.

Plant Chemical Analyses

Plant forage and root samples of crops grown in the greenhouse were dried at 70 C and ground in a Wiley mill to pass a 20-mesh screen. One gram of plant sample, if available, was dry-ashed in a muffle furnace, first at 200 C for 30-60 min and then at 450 C for 1-2 hr. The salts were dissolved in HCl and diluted to a volume of 100 ml 0.1*N* HCl, following the procedure described by Jackson (72). Root samples were corrected for soil contamination. Phosphorus, K, Ca, Mg, and the micronutrients Zn, Mn, Cu, Fe, and Al were determined in these solutions.

Phosphorus was determined colorimetrically by the molybdenum blue color method of Fiske and Subbarrow (47). Potassium was determined with a Beckman 2-Du Flame Spectrophotometer (72). Calcium, Mg, and the micronutrients were determined with a Model 303 Perkin-Elmer Atomic Absorption Spectrophotometer. For the Ca determination, lanthanum oxide was added to the solution to give a concentration of 1,000 ppm La to prevent P interference, as described by Breland (25).

Greenhouse Investigations

Paleton clay loam and sandy loam were the only soils investigated in greenhouse experiments. The same techniques were used for all experiments. Plastic pots of 15 x 12.5 x 15 cm dimensions with holes 1 cm square close to the bottom were used as containers. Approximately 750 g of well-washed gravel were placed in each pot. Fertilizer salts were applied by spraying a water solution onto the soil spread in a thin layer on a table while being repeatedly turned with a trowel. Two kilograms of surface soil from Profile I and 3 kg of subsoil from Profile I and the two horizons of Profile II were used per pot.

The pots with soil were placed on concrete benches in a greenhouse. Tomato (*Lycopersicon esculentum*), pangolagrass (*Digitaria decumbens* Stent.), hairy indigo (*Indigofera hirsuta*) and pigeon pea (*Cajanus cajan* var. Norman) were used as test plants. Pots were watered as often as needed with distilled water. The drainage water from each pot was collected in a plastic saucer and returned to the pot in order to prevent loss of nutrients.

Plant tops and roots,were dried at 70 C for 48-72 hr, weighed, ground in a Wiley mill to pass through a 20-mesh screen, mixed and stored for chemical analyses. Roots were washed thoroughly to remove soil and other debris. Results were calculated on oven-dry plant weight basis.

Exploratory Nutrient and Nutrient Residual Study

Tomato plant response

This experiment was initiated to assess the general fertility status of two selected Pueltan soils, as well as the residual effects of added fertilizers by growing successive crops. The experiment consisted of 8 treatments (N, P, K, PK, NK, NP, NPK, and a control 0) with 3 replications. Surface and subsoils were limed at 3 rates, 0, 4,480 and 8,960 kg/ha for Profile I and 0, 2,240 and 4,480 kg/ha for Profile II. A basic treatment of all other elements, including micronutrients, was applied to all pots. A total of 288 pots was prepared. The amounts of nutrient elements applied per pot and their sources are given in the following Table (Table 7):

Table 7.--Nutrient quantities and sources for exploratory study.

Nutrient	Application rate kg/ha	Nutrient source	Applied Nutrient ------ g/pot	 Source ------
N	275	NH_4NO_3	0.61	1.74
P	150	$Na_2HPO_4.12H_2O$	0.73	3.67
K	412	KCl	0.91	1.44
Mg	275	$MgSO_4.7H_2O$	0.61	3.71
Fe	55	$FeC_6H_5O_7.3H_2O$	0.12	0.66
Mn	40	$MnSO_4$	0.091	0.174
Zn	20	$ZnSO_4.7H_2O$	0.046	0.16
B	4	$Na_2B_4O_7.10H_2O$	0.009	0.049
Cu	4	$Cu(C_2H_3O_2)_2.H_2O$	0.009	0.028
Mo	4	$Na_2MoO_4.2H_2O$	0.009	0.015

Preparation of pots and fertilizer application proceeded as previously described. Fifteen to 20 seeds of tomato var. Rutgers were sown in each pot. Germination was uniform in the clay loam soil and irregular in the sandy loam soil. It was necessary to reseed the sandy loam soil until a uniform stand was obtained. Possibly the low water holding capacity of this soil accounted for irregularity of germination. Eight days after germination, seedlings were thinned to 5 per pot except for those pots lacking P, where the total number of germinated plants was grown in order to obtain sufficient plant material for analysis.

Plant tops and roots, were harvested at the flowering stage after

74 days of growth (5 January to 20 March 1967). Soil samples were taken for laboratory determinations. The remaining soil and gravel were separated and returned to the pots.

Pangolagrass plant response

Pangolagrass was immediately planted as a second crop. Two uniform stolons were planted per pot. Twenty days after the first harvest, plants started to show foliar symptoms of N and K deficiencies. These were corrected by adding N and K fertilizers in amounts equivalent to the original applications. No other fertilizers were applied.

The forage was harvested at a height of 3 cm above the soil surface after 45 days' growth (6 May to 21 June 1967) and after an additional 60 days (21 June to 22 August 1967). Roots were collected following the last forage harvest. Soil samples were taken from each treatment for laboratory determinations. The remaining soils were again returned to the pots.

Hairy indigo plant response

Hairy indigo was planted as the third crop. About 20 seeds were sown in each pot. Seedlings were thinned to 8 per pot 1 week after the seeds had germinated, except in those pots lacking P, where the maximum number of plants was grown in order to have sufficient material for analysis. A suspension of plant inoculum was applied on top of the soil in those pots lacking N, when the seeds had germinated. The indigo plants were harvested after 90 days of growth (7 September to 10 December 1967) and roots were removed. Final soil samples were taken for laboratory analysis.

Lime and Phosphorus Study

Pangolagrass plant response

The experimental design was a 4 x 4 factorial with 4 rates of lime and P applied to surface soils of the same soil profiles investigated in previous experiments. Each pot also received a basic treatment consisting of all other nutrient elements according to Table 8.

Two uniform pangolagrass stolons were planted as the first crop. Three harvests were made, after 39 days' growth (3 May to 11 June 1968), after an additional 38 days' growth (11 June to 18 July 1968), and 33 days after the second harvest (18 July to 20 August 1968). Soil samples were taken after the first and third harvests for laboratory determinations. Roots were removed after the third harvest.

Pigeon pea plant response

Pigeon pea was planted after the pangolagrass was removed. Eight inoculated seeds were sown in each pot. After 8 days, seedlings were thinned to 5 per pot. Twenty days before harvest, K fertilizer was added in amounts equivalent to 150 kg/ha to all pots containing sandy loam soil, which helped to overcome a K deficiency shown by the plants. Plant tops and roots were harvested at the flowering stage after 43 days of growth (26 August to 9 October 1968). Soil samples were taken for laboratory determinations after plant harvest.

Table 8.--Nutrient quantities and sources for the lime-phosphorus study.

Nutrient	Application rate	Nutrient source	Applied			
			Sandy loam		Clay loam	
			Nut	Source	Nut	Source
	kg/ha		g/pot			
N	300	NH_4NO_3	0.45	1.34	0.03	0.89
K	400	KCl	0.60	0.95	0.40	0.63
Mg	300	$MgSO_4.7H_2O$	0.45	2.70	0.30	1.82
Fe	55	$FeC_6H_5O_7.3H_2O$	0.08	0.32	0.055	0.21
Zn	20	$ZnSO_4.7H_2O$	0.03	0.106	0.02	0.07
Mn	40	$MnSO_4$	0.06	0.16	0.04	0.106
Cu	4	$Cu(C_2H_3O_2)_2.H_2O$	0.006	0.015	0.004	0.01
Mo	4	$Na_2MoO_4.2H_2O$	0.006	0.01	0.004	0.007
B	4	$Na_2B_4O_7.10H_2O$	0.006	0.032	0.004	0.021

	Application		
	Sandy loam	Clay loam	Nutrient source
	kg/ha		
Lime	0	0	$CaCO_3$
	1500	4000	
	3000	8000	
	4500	12000	
P	60	60	Triple superphosphate
	120	120	
	180	180	
	240	240	

RESULTS AND DISCUSSION

Field Work

Description of Soil Profile Features

Detailed notes on the appearance, texture, structure, and consistency of the soil comprising the various layers that were differentiated and demarcated within the soil profiles at Sites I and II are given in the Appendix Section. No detailed description was attempted in the case of other Puletan soils since these samples were taken exclusively for the purpose of physical and chemical analyses.

Profile I

The original soil map of British Honduras, showed that the soil represented by Profile I, in the Belize area, chiefly occurred north of the Belize-Hattieville-Cayo road and west of the Hattieville-Boom road. In some areas, this soil occurred in combination with other Puletan soils, particularly with Puletan coarse sand, 53b and Puletan sandy silt (53a).

The site selected for sampling was located in a flat area occupied mainly by sedges and savanna grasses. Nearby, patches of Broken Pine Ridge vegetation were quite common, Palmetto (Trinax wendlandiana Bec. and T. argentea) and pines (Pinus caribaea M.) were typical.

The soil profile showed a thick humic dark surface layer, 0-15 cm of clay loam texture, with abundant grass roots. The color of the upper part of the soil profile changed from dark brown to black, when wet, to light brown when dry. Below the 15 cm depth to 27.5 cm, the color changed to even lighter brown showing a sparse red and yellow mottling. The texture of this second layer was the same as that of the top layer. Changes in color and texture became clearer in the third layer, being light yellow and with higher clay content than the above layers. Gley features were present though not intense, along with red and yellow mottlings. Deeper still in the profile the soil changed abruptly to a reddish color with very high clay content. Gley and yellow mottlings were typical and abundant.

The structure of the soil was granular throughout the profile, fairly strong, and water-stable. The aggregates, when rubbed with water between finger and thumb, broke into smooth paste having paler color than the aggregates which is a characteristic feature of pseudosand. The consistency of the soil was sticky and plastic, this feature was more marked below the 27.5 cm depth. When dry these soils were rather hard, especially in the clayey horizons.

The presence of gley, and red and yellow mottling in the profile below the 15 cm depth, indicated the occurrence of reducing conditions within the zone of saturation by fluctuating ground-water. This soil profile was sampled under persistent rain. In fact, the entire profile was waterlogged and water trickled constantly from the bottom and the sides of the profile after water had been bailed out with a bucket.

Profile II

The soil represented by this profile occurred particularly in the area located north of the Belize-Hattieville road and east of the Hattieville-Boom road. It may occur in some other isolated areas in combination with other Puletan soils, like Puletan sandy silt 53e or Puletan loamy sand 53a.

This soil was sandy in texture. The surface layer, 0-15 cm, consisted of sandy loam with abundant small grass roots. The color was rather gray and became lighter when dry. The sand consisted mainly of quartz and the structure was typical single-grain. Below the surface layer, the soil became finer in texture, though still sandy and the color was paler than the surface layer. However, the structure remained the same. Deeper still and all the way to 90 cm depth, the soil was sandy though finer in texture, changing in color to yellow with marked red and yellow mottlings and some gley, clear indications of the presence of a fluctuating water table. The consistency of the soils was non-sticky, non-coherent, and friable both when wet or dry. An outstanding feature of this soil was compaction which markedly increased in the 30-60 cm depth layer.

This soil profile was also sampled under persistent rain. The heavy rainfall made possible observation of the extremely slow downward percolation of water through the compacted layer, 30-60 cm depth. Consequently, water that passes through the 0-30 cm layer either must build up or run laterally on top of the compacted layer, depending on the slope of the soil. Below the 60 cm depth, compaction decreased noticeably and water trickled constantly both from the bottom and the sides of the pit. In some instances, one side of the pit slipped down,leaving a concave surface which made sampling work difficult.

Drainage

Typical hydromorphic features observed in Profiles I and II, namely, grey gley, and red and yellow mottling below the surface layer, provided evidence that low rate of percolation relative to rainfall intensity caused waterlogging, a characteristic of these soils, especially during the rainy period. These characteristics were mentioned by other investigators (34, 60, 158). The occurrence of water tables also served as an indication of restricted drainage.

Water tables may be either permanent (true) or temporary (perched), the first being associated with depressed or flat topography, and the second with compaction of the subsoil. The latter may be the predominant type in the Puletan soils. At the time of sampling, the water table was within the 0-90 cm depth, since water had to be bailed out constantly in order to take soil samples. Field work was conducted at the beginning of the rainy season; therefore, as the season precedes, water tables should rise and reach the soil surface where depressions occurred. In the areas examined, hydromorphic features were absent in the surface layer, 0-15 cm, indicating that superficial waterlogging was not likely to occur, at least for extended periods of time.

Direct observations made in the field at the time of sampling, and results of laboratory investigations which will be later described, provided evidence for the difference between the two sampled soils, although they were considered as components of only one textural type, namely, Puletan sandy loam. Visual observation of the original soils map gave indication that the area of soil represented by Profile II was greater than the area represented by Profile I. Both occupy a total of 36,721 ha in the country. Approximately 70% of that area is concentrated close to Belize City and included the soils selected.

Laboratory Investigations

Soil Physical Measurements

Textural classification data showed that coarse texture was predominant among the Puletan soils (Tables 9, 35). In fact, about 80% of the total area occupied by these soils, comprised soils between the sandy loam and sandy clay loam texture. About 20% was clay loam and clays.

The textural classification, according to this investigation, was somewhat different than that given by Wright et al. (159) in Table 10.

The possible explanation for these differences is that textural classifications given by Wright et al. were probably estimated directly in the field by feel, as is usually done in soil survey work. The textural data presented here were obtained in the laboratory by mechanical analysis. The soil was submitted to drastic dispersion with the addition of an excess of dispersing solution in order to break down the highly aggregated soil. It is likely that data obtained by the laboratory method will show higher percentages of silt and clay than sand. Unfortunately, Wright et al. did not state which of the two methods they used.

The data for particle size distribution showed that in almost all the coarse textured soils, 50% or more of the total sand fraction consisted of fine and very fine sand. The preponderance of fine sand may explain the high compaction shown by the sandy soils. Particles of this size may fill the pore spaces left by larger particles, leaving small spaces which will not only retard the passage of water but will also make difficult the penetration of plant roots.

Table 9.--Textural classification of Puletan soils.

Soil	Soil Depth	*Sand						Silt	Clay	Textural Classification
		V.C	C	M	F	V.F	Total			
	--- cm ---	%								
				PROFILE I						
53_c	0-15	--	0.9	14.6	17.7	2.4	35.6	30.8	33.6	Clay loam
	15-27.5	--	2.1	3.4	17.0	10.7	33.2	32.0	34.8	" "
	27.5-37.5	2.0	9.0	4.0	7.4	9.8	32.2	23.0	44.8	Clay
	37.5-90	0.2	0.6	0.3	1.1	1.0	3.2	20.0	76.8	"
				PROFILE II						
	0-15	1.9	14.4	14.7	43.4	1.4	75.8	12.0	12.2	Sandy loam
	15-30	2.5	20.2	11.2	23.1	10.2	67.2	19.2	13.6	" "
	30-45	1.9	11.2	12.0	32.5	7.0	64.6	19.6	15.8	" "
	45-60	2.2	13.0	12.6	23.1	13.6	64.4	19.6	16.0	" "
	60-90	2.6	15.1	12.6	31.0	11.5	72.8	18.2	9.0	" "

*Abbreviations: V.C = very coarse (2.0-1.0 mm), C = coarse (1.0-0.5 mm)
M = medium (0.5-0.25 mm), F = fine (0.25-0.1 mm)
V.F = very fine (0.1-0.05 mm)
Silt = 0.05-0.002 mm
Clay =< 0.002 mm

Table 10.--Comparative textural classification of Puletan soils.

	Texture	
Soil	Given	Actual
53	Loamy sand	Sandy clay loam
53b	Loamy sand	Sandy loam
53c	Sandy loam	Sandy loam and clay loam
53d	Loamy coarse sand	Sandy loam
53e	Silty sand loam	Sandy clay loam
53f	Clay	Clay

Assuming that the particles of fine and very fine sand are spherical in shape, it is possible to expect a maximum hexagonal packing arrangement, which is the most compact packing of single particles. The size of a single pore which is subtended by 3 uniform spheres in hexagonal packing is determined by the size of the individual spheres. By Slichter's formula, $d=D\times0.33$, which expresses the relationship between the diameter of the soil pores (d) and the diameter of the individual soil particle (D), the pore sizes to expect in a soil formed entirely by particles between 0.25 and 0.05 mm size (fine and very fine sand) will be of 0.082 and 0.0165 mm diameter. In the literature (152, 155) it was found that for finer grass roots the diameter of the soil particles should be not less than 0.3 mm. The grade of material within this critical size is that of medium sand (0.5-0.2 mm).

In Pulaten sandy soils, the size of the pores within the compacted layers (0.30-0.60 cm depth) could be larger than the theoretical calculated value due to mixture with other size particles which would alter the general packing of the soil particles, but not sufficiently to eliminate soil compaction.

In Profile I, the texture changed noticeably with depth from clay loam to clay. In Profile II, texture was uniform sandy loam throughout the entire profile.

Bulk density and subsequent physical determinations were performed only for samples taken from Profiles I and II (Table 36). The values for bulk density for soil samples representing the different layers of the 2 soil profiles may be employed to assess root penetrability by applying the criteria suggested by Vehimeyer and Hendrickson

(145), namely, 1.46 to 1.63 for silty and clayey soils and 1.75 for sandy soils.

Bulk density varied considerably between and within profiles due to changes in texture and compaction with increased depth. In Profile I bulk density values were within the range established by Vehimeyer and Hendrickson. The lowest was 0.85 for the surface layer; it increased with depth to the highest value of 1.52 at 27.5-37.5 cm. These values were doubtless caused by the marked aggregate structure (Pseudosand) which was a characteristic of these clayey soils. The Puleton soils of the clay loam texture should not offer any mechanical impedence to root penetration within the 0-90 cm depth.

In Profile II, except for the surface layer with bulk density of 1.48, the remainder of the profile had higher values than the critical range established by Vehimeyer and Hendrickson. The values varied from 1.90 to 2.01 and increased with depth, probably due to compaction by the pressure exerted by the overlying layers. Consequently, mechanical impedence to root penetration may occur in this and other similar soils.

Only the total pore space of the top layer (0-15 cm) of Profile I exceeded 66%, which is considered necessary for an ideal soil (Table 37). This value was 66.4% which corresponded to a bulk density of 0.85 and a particle density of 2.53. The remainder of the samples gave values considerably lower than 66%, especially in Profile II, where the highest value was 44.8% and the lowest 24.5%.

In Profile I, values for capillary pore space were the same from 0 to 37.5 cm depth. Below this depth, values increased doubtless due to an increase in the clay content of the soil and subsequent decrease in sand content (Table 37). In Profile II, capillary pore space values were very low, varying from 0.9 to 5% due to high sand and low clay content. Its capacity for storing water should be small (Table 37).

Non-capillary pore space was assessed by the difference between total pore space and capillary pore space. Its value indicates not only the amount of root room within the successive layers of the soil profile, but also the dimensions of the channels down which water can freely move under the pull of gravity and the maximum degree of soil aeration possible in the fully drained soil.

The profile diagrams, Fig. 3, clearly illustrate the variation in magnitude of the non-capillary pore space in each soil. The general cross sectional shape of the non-capillary pore space is indicated by the middle area in each profile diagram. According to the laboratory data, Profile I, which had an increasing amount of clay with depth, presented a non-capillary pore space of funnel shape, that is, wide open in the surface layer and narrowing with depth until it was closed below 37.5 cm. The greater value of the non-capillary pore space in the top layer was probably due to the high organic matter content plus a relatively high sand content. In Profile II, non-capillary pore space was of the parallel chimney shape, uniform through the entire profile. Internal drainage impedance is most likely to occur where the non-capillary porosity has least magnitude and where its value diminishes down the profile (funnel shape).

However, it was demonstrated earlier that soils of Profile II and others having the same characteristics may also show impeded internal drainage due to high compaction which may not effect the

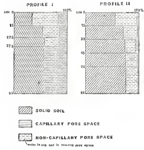

Figure 3.—Soil water and soil air profiles.

total air volume present in the non-capillary pore space. It might affect the pore sizes, thus affecting the rate at which water percolates through the profile The amount of free water which remains in the non-capillary pore space when the soil is wetted by rain provides a further indication of the degree of drainage impedence. Pit sampling was carried out under rainy conditions, and according to the profile diagrams the non-capillary pore space of all the soil samples contained excessive amounts of free water which apparently was draining very slowly.

Determinations of sticky point and index of texture were closely related and depended on the amount of clay present in the soil (Table 38). In Profile I, sticky point and index of texture were higher in the surface layer and below 37.5 cm.possibly due to high organic matter content in the surface and the high clay content in the subsoil. In Profile II, values for both determinations were almost constant in the entire profile. The texture in this profile was sandy loam. The values for sticky point and for index of texture were within the range established for sandy soils.

The results from X-ray diffractograms for surface soil and subsoil of Profiles I and II are listed in Table II. Peaks obtained for Mg and K saturated clays were similar as shown in Figs. 4 and 5.

The surface soil from Profile I presented peaks at 10.3, 7.3, 5.0, 3.6 and 3.3A which indicated the presence of halloysite, kaolinite, muscovite, metahalloysite, and quartz, respectively. This distribution also applied to the subsoil.

The surface soil from Profile II had peaks at 7.3, 4.3, 3.6, 3.3 and 3.2A which corresponded to kaolinite, gibbsite, metahalloysite, Table 11.--Clay minerals present in Puletan soils.

Spacing --Å--	Topsoil	Subsoil
	PROFILE I	
10.3	Halloysite	Halloysite
7.3	Kaolinite	Kaolinite
5.0	Muscovite	Muscovite
3.6	Metahalloysite	Metahalloysite
3.3	Quartz	Quartz
	PROFILE II	
7.3	Kaolinite	Kaolinite
4.3	Gibbsite	
3.6	Metahalloysite	Metahalloysite
3.3	Quartz	Quartz
3.2	K feldspars	

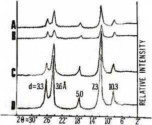

Figure 4.--X-ray diffractogram - Profile 4.
Curve A = K saturated - surface soil.
Curve B = Mg " - " ".
Curve C = K " - subsoil.
Curve D = Mg " - " .
2θ = Diffraction angle in degrees.
d = Interplanar spacing in Å.

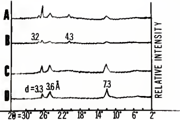

Figure 5.--X-ray diffractogram - Profile II.
Curve A = K saturated - surface soil.
Curve B = Mg " - " " .
Curve C = K " - subsoil.
Curve D = Mg " - " .
2θ = Diffraction angle in degrees.
d = Interplanar spacing in Å.

quartz, and K feldspars, respectively. The subsoil samples showed peaks at 7.3, 3.6, and 3.3A, which indicated the presence of kaolinite, metahalloysite, and quartz, respectively.

Results showed predominance of kaolinitic clay in both soils, which should be expected considering the humid climate prevalent in the Belize area for most of the year. Data were also in apparent agreement with Wright et al. (159) who reported X-ray data for Puletan soils showing kaolinite and metahalloysite as the predominant clay minerals present. Contrary to Wright's report, montmorillonitic clays were not detected. This type of clay is likely to be formed in humid climates under impeded soil drainage conditions, characteristic of Puletan soils.

The fact the kaolinite was consistently present in Puletan soils, supported the contention of Wright et al. (159) that Puletan soils were highly weathered and in an advanced stage of maturity. Kaolinite formation in these soils was probably due to a process of desilication in which Si dissolved and remained soluble until drainage water removed it. According to Mohr and van Baren (95) complete removal of Si by intensive desilication could take place only when the soil was permeable and subject to leaching losses. In the case of Puletan soils, Si may not have been removed completely because of impermeability of the subsoils, as was demonstrated earlier. This may have resulted in an intermediate desilication and consequent formation of kaolinitic clay.

Soil Chemical Measurements

Chemical determinations of Puletan soils are given in Tables 12, 39, 40, 41. Standards for comparison and assessment of the results are given at the bottom of Tables 12 and 39. In general, pH

Table 12.--Chemical analysis of Pulatan soils.

Soil	Depth	pH H₂O	pH KCl	O.M.	N	C/N	Av. P	Org. P	Exch. Cap.	Ca	Mg	K	Na	Base Sat.	Ca/Mg	Mg/K	Ca+Mg/K
	-- cm --			--- % ---			-- ppm --		-------- me/100g --------					%			
								PROFILE I									
53c	0-15	4.9	4.3	5.59	0.21	16.5	7.2	42.7	9.6	0.71	0.34	0.14	0.46	17.2	2.09	2.43	7.5
	15-27.5	5.0	4.3	1.05	0.10	6.0	8.0	5.5	4.9	0.38	0.20	0.10	0.33	20.6	1.90	2.00	5.8
	27.5-37.5	5.0	4.2	--	--	--	7.2	--	5.6	0.46	0.49	0.10	0.04	19.5	0.10	4.90	9.5
	37.5-90	4.7	4.1	--	--	--	14.0	--	13.1	1.94	1.32	0.20	0.64	31.3	1.47	6.60	16.3
								PROFILE II									
	0-15	5.5	5.1	1.58	0.10	10.9	8.8	2.5	2.1	0.45	0.15	0.06	0.30	45.7	3.00	2.50	10.0
	15-30	5.5	5.2	--	--	--	10.0	--	1.4	0.54	0.16	0.09	0.33	80.0	3.37	1.78	7.8
	30-45	5.2	4.7	--	--	--	7.6	--	1.6	0.46	0.15	0.05	0.28	58.7	3.00	3.00	12.2
	45-60	5.2	4.6	--	--	--	6.0	--	1.6	0.40	0.15	0.11	0.36	63.7	2.67	1.36	5.0
	60-90	5.0	4.6	--	--	--	6.0	--	1.3	0.54	0.14	0.04	0.05	58.2	3.86	3.50	17.0
								Standards for Comparison (0-15 cm)									
High		7.5		7.0	0.35	11.5	52			24.0	6.00	0.55			--	--	--
Medium		6.5		3.5	0.20	10.0	21			12.0	3.00	0.35			4.00	8.00	40.0
Low		5.0		0.7	0.05	8.5	9			4.0	1.00	0.20			--	--	--
									(0-30 cm)								
High		7.5		5.2	0.26	11.5	39			18.0	4.50	0.41			--	--	--
Medium		6.5		2.6	0.15	10.0	15			9.0	2.30	0.26			4.0	8.0	40.0
Low		5.0		0.6	0.04	8.5	6			3.0	0.80	0.15			--	--	--

of the Puletan soils was medium-low to very low, ranging between 4.7 and 5.6. Generally pH values for surface soils were slightly higher than those of deeper layers. Soils with more sandy texture showed more uniform pH distribution, ranging between 5.0 and 5.5. The generally low pH values were most likely the result of climate and type of soil parent material. Leaching of bases occurs under heavy rainfall, as in British Honduras, whereupon the soil colloidal exchange sites become largely occupied by H and Al. Soil pH in H_2O was appreciably higher than in KCl; the difference indicated possible rapid Al ion liberation into solution.

Organic matter concentration in most of the soils ranged from medium to low, diminishing consistently with depth. Profile I had a rather high concentration of 5.99% in the surface layer. The concentration diminished to 1.05% in the 15-27.5 cm layer and was not measurable at lower depths. Profile II contained only 1.58% in the surface layer and none at lower depths.

Total N concentration of Puletan surface soils ranged from 0.30 to 0.22%. Nitrogen concentration of surface layers was higher in every case which reflected their organic matter content. Profile I had a high N concentration, 0.21% in the surface layer, while soils of Profile II showed a value of 0.10%. The higher N content of Profile I, besides being related to organic matter content may also be a result of non-symbiotic N fixation by blue-green algae, which was noticeable in wettest areas. Algae were also noticed in greenhouse pots.

Most of the Puletan soils had C/N ratios slightly higher than the critical value of 10 (138), particularly in the surface layers, which denoted the existence of incompletely decomposed plant residues.

Total P values ranged from 28 to 124 ppm in the surface soil and from 24 to 68 ppm in the 15-30 cm layer depth. These low values were to be expected in Pulatan soils as well as in most of the soils of British Honduras, since they were derived mainly from acid igneous, metamorphic, and sedimentary rocks that are low in phosphates. Because of the absence of a mineral source it would be logical to assume that the greater part of soil P was derived from readily mineralizable organic materials. Organic P was low, and, as expected, it was higher where the organic matter content was high. Organic P diminished markedly with depth. Truog's available P was low in every soil, which agreed closely with previous analysis by Hardy et al. (60) and Romney (121).

The CEC in general was low ranging from 2.4 to 9.6 meq/100 g in surface soils. The low CEC was probably due to the following factors:

1) Greater part of the clay fraction was made up of 1:1 clay minerals.
2) Low soil pH.
3) High Al content which tended to form $Al(OH)_3$ and block exchange sites.
4) The sandy texture in the majority of the soils.
5) Intense weathering.

The CEC was generally higher in the surface soil since it is closely related to the organic matter produced by the processes of cycling and decomposition. CEC decreased in the 15-30 cm layer due to low organic matter content and tended to increase again in deeper horizons where clay content increased, especially in soils type 53f and soils of Profile I.

Unfortunately there are no standards by which to judge the values found for total Ca, Mg, K, and Na. Therefore, the data obtained can only be interpreted in relation to their exchangeable forms. However, the potential of these soils to produce crops without fertilization, in terms of these elements, is obviously limited.

In general, exchangeable Ca, Mg, and K were extremely low. In Profiles I and II, Ca did not vary drastically in the surface as compared to that of deeper layers and in both profiles the 90 cm layer showed higher Ca content than the upper layers. This finding agrees with Charter's contention (34) that these soils could be enriched by Ca-charged groundwater from deeper underlying calcareous sediments.

Exchangeable Mg values were very low in all soils, the source of this element should be granitic rocks. Exchangeable K was also very low. Its source is K-bearing minerals such as feldspars, muscovite, and biotite whose presence in these soils was indicated by X-ray diffraction analysis. There was no definite pattern in the distribution of K in the profile. The slightly higher K content of some surface layers was probably a result of translocation of K by vegetation from the subsoil to the surface.

Both total and exchangeable Na appeared to be high in Puletan soils. The source of Na in these soils is most likely such minerals as feldspars. Also it is possible that salts may have intruded in these savanna soils during hurricanes. As Na is considered nonessential for most plants, a lower critical limit has not been set for plant growth. However Na may have an indirect beneficial effect on the growth of certain forage grasses, such as pangolagrass, by substituting for a part of the K requirement.

Gammon (54) showed that pangolagrass had a very high K requirement for maintenance of maximum growth, but that Na was capable of substituting for approximately two thirds of the K requirement without causing any appreciable reduction in growth.

Sodium possibly helps to reduce soil acidity so that the environment is maintained suitable for most crops despite the possible high Al and Fe content. On the other hand, it is possible in sandy soils that Na may leach out of the profile more rapidly than K. Sodium may also exert important undesirable effects on plant growth through adverse modification of soil structure. The high Na content in these soils may enhance impermeability and waterlogging conditions. In Profiles I and II, the increase in soil compaction with depth ran parallel to exchangeable Na content.

Calculation of relative ratios of exchangeable Ca, Mg, and K showed the existence of great imbalance among the 3 elements. Exchangeable Mg appeared to be high relative to Ca, and K was higher than Ca and Mg. Profile II showed Ca and Mg ratios closer to the desirable value than Profile I.

Although micronutrients play an important role in plant nutrition, analysis for total micronutrients is seldom conducted routinely. Thus, it was difficult to find soil micronutrient data for comparative purposes. The Fe, Cu, Mn, and Zn concentrations in the Puletan soils could be adequate for crop growth. No plant deficiency symptoms were noted in greenhouse experiments as will be later discussed. Total and exchangeable Al appeared to be high. High Al may be characteristic of other soils in British Honduras and may explain the presence of Al indicator plants such as Miconia reported by Wright et al. (159).

Aluminum may in great part be responsible for the high acidity of the Puletan soils. The low available P is no doubt partially due to fixation by Al and Fe. Aluminum as earlier stated is also probably responsible for the low CEC of these soils. Al^{3+} is held so tightly that the effective exchange capacity is strongly reduced (84). Many tropical soils are inclined to become Al toxic as Al dominates and blocks the exchange complex after removal of bases by heavy leaching.

Phosphorus Fixation and Phosphorus Fractionation Studies

All soil P fractions of Profile I, except water soluble-P were higher than P fractions of Profile II soils (Table 13). This was expected on the basis of their chemical properties. Lime increased P in all fractions in Profile I. The increases in Fe- and Ca-P fractions were statistically significant at the 5% level of probability. In soils of Profile II, there was also an increase in all P fractions. The P fixation capacity of soils of Profile I was considerably larger than that of Profile II. Furthermore, the fixation capacity of both soils appeared to be closely related to their KCl and HCl extractable Al. Correlation coefficients (r) were 0.97 and 0.95 for Profile I soils and 0.66 and 0.67 for Profile II soils.

In both soils most of the P fixed was found in the Al- and Fe-P fractions (Tables 14 and 15). This was undoubtedly due to precipitation or adsorption of the applied P by Fe and Al present in the soil. In soils of Profile I, lime had a highly significant effect in increasing the Al-P and the Fe-P fractions. However, a decrease in fixation was noticed at the highest level of lime (pH 6.2) indicating the possibility of a decrease in the solubility of both Al and Fe, due

Table 13.--Phosphorus fractions in Puleton soils.

Soil	Depth	H_2O-sol-P	Al-P	Fe-P	Ca-P
	--- cm ---		ppm		
53	0-15	0.08	1.9	3.8	0.92
	15-30	0.08	0.8	3.8	0.92
53a	0-15	0.08	1.6	2.6	0.80
	15-30	0.08	0.8	4.1	0.80
53d	0-15	0.06	3.7	1.8	0.72
	15-30	0.06	2.4	1.2	0.45
53e	0-15	0.16	3.1	6.4	0.94
	15-30	0.16	2.7	4.0	0.90
53f	0-15	0.08	5.1	16.0	4.4
	15-30	0.08	2.0	8.0	4.8
			Profile I		
53c	0-15	0.08	7.03	7.71	2.39
	15-27.5	0.08	4.00	9.00	3.40
	27.5-37.5	0.08	4.00	7.40	5.20
	37.5-90	0.08	4.00	12.60	5.50
			Profile II		
	0-15	0.08	2.70	0.52	1.20
	15-30	0.08	2.80	0.80	1.10
	30-45	0.08	1.20	1.40	0.90
	45-60	0.08	1.20	2.60	0.80
	60-90	0.08	1.20	1.90	1.20

Table 14.--Phosphorus fractions and pH before P treatment.

Lime applied	H_2O sol-P	Al-P	Fe-P	Ca-P	pH
kg/ha			ppm		
		PROFILE I			
None	0.08	7.03	7.71	2.39	5.0
2000	0.37	11.76	8.87	2.82	5.7
4000	0.69	12.77	7.92	2.91	6.2
		PROFILE II			
None	0.08	2.70	0.52	1.20	5.6
1000	0.45	3.30	0.53	1.10	6.5
2000	1.20	4.00	1.05	1.20	7.4

Table 15.--Phosphorus fractions after P treatment and P removed.

Lime applied	Al-P	Fe-P	Ca-P	P removed
kg/ha		ppm		
		PROFILE I		
None	104.16	46.21	2.60	163.5
2000	209.37	90.60	4.72	295.5
4000	191.57	84.40	5.19	279.0
		PROFILE II		
None	5.6	3.4	1.25	21.8
1000	8.9	3.2	1.36	22.4
2000	9.6	4.1	1.78	30.5

to higher pH. Lime had a similar effect in soils of Profile II, with most of the increase found in the Al-P fraction. The increase in the Ca-P fraction was also statistically significant. The increase in the Fe-P fraction was apparent though not significant.

The fact that most of the fixed P appeared in the Al-P fraction could be explained from two points of view:

1) The clay fraction of both soils was mainly kaolinitic as shown by X-ray diffraction analysis. The importance of kaolinite in P fixation has been stressed by various investigators (79, 113). They claimed the Al ions may be dissociated from this mineral and combined with P to form Al-P which in turn causes more kaolinite to dissociate.

2) Field observations and laboratory analyses have demonstrated that these soils are characterized by having poor internal drainage. In poorly drained soils, Al is present in amorphous minerals (43), while in well-drained soils they are crystalline. The former react more readily with P than the latter because of their greater surface.

The difference in the Fe-P fraction encountered in these soils was probably caused by the higher Fe content in Profile I soils than in Profile II soils.

Organic matter content may also have been partially responsible for the difference in the P fixation capacities of these soils. In sandy soils, Hortenstine (70) found no effect of organic matter on P fixation. Leon fine sand, which is characterized by a rather high organic matter content compared to Lakeland sand and Pulaton loamy fine sand, had the lowest P fixation capacity.

Lime affected P fixation differently in these soils, ie

Profile I, the highest lime level decreased P fixation. In Profile II, pH as affected by lime did not seme to be the controlling factor. Where highest P fixation occurred, pH was slightly over neutrality. Hence, in soils of sandy texture, factors other than pH, such as type of clay and Al content may be the factors controlling P fixation.

Mobility of Phosphorus in Puletan Soils

The data obtained in these laboratory studies are presented in Tables 16 and 17 and depicted in Figs. 6 and 7.

Experiment I

To leach the soil, 850 ml of distilled water were applied in 7 successive additions varying between 30 and 200 ml each. The total amount of P leached from these soils was very low, in some cases it was hardly detectable in the leaching. The rate at which P was fixed also appeared to be high as indicated by the low P concentration in every leaching (Tables 42 and 43). Only 0.80% and 0.40% were leached when 60 and 120 ppm P were applied to unlimed soils While lime significantly increased the concentration of P in the leaching to 1.35 and 0.70% for the 60 and 120 ppm P applications, losses were very low (Table 16 and Fig. 6).

The total P concentration in each of the 3 portions of the soil columns showed that fixation occurred mostly in the top 4 cm layer. In unlimed soil, 76% and 58% of the applied P was retained by the surface soil for rates of 60 and 120 ppm P In limed soils, 78% and 77% was retained. The concentration of fixed P consistently decreased with depth in the soil column (Table 44).

Fractionation of selected samples showed that in unlimed soils

Table 16.--Phosphorus recovered in leaching from surface soil.

Applied		Recovery	
Lime	P	Total	Percentage
kg/ha	--ug--	--ug--	----%----
		PROFILE I	
None	None	3.3	--
None	6000	48.0	0.80
None	12000	48.0	0.40
12000	6000	81.2	1.35
12000	12000	84.5	0.70

Table 17.--Phosphorus recovered in leaching from surface soil.

Applied		Recovery	
Lime	P	Total	Percentage
kg/ha	--ug--	--ug--	----%-----
		PROFILE II	
None	None	77.9	--
None	6000	5650.9	94.1
None	12000	10711.5	89.0
4500	6000	4528.7	75.2
4500	12000	7993.0	66.4

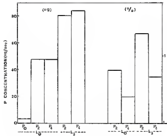

Figure 6.--Phosphorus recovered in leaching from surface soil - Profile I.

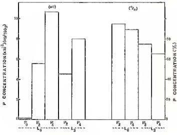

Figure 7.--Phosphorus recovered in leaching from surface soil - Profile II.

receiving 120 ppm P, 52% of the total P fixed was present in the Al-P fraction, 42% as Fe-P, and the remainder as H_2O-soluble P and Ca-P. In soils limed at the rate of 12000 kg/ha and fertilized at the rate of 120 ppm P, 54% of the total P fixed was in the Al-P fraction, 38% as Fe-P, and 7 and 1% as H_2O-soluble P and Ca-P, respectively (Table 45). As in previous laboratory studies lime decreased P fixation and increased P concentration in the leachings. Most of the fixed P was present in the soil as Al-P and Fe-P.

Unlimed and limed (4500 kg/ha) surface soil from Profile II was also used in this experiment. Phosphorus was applied at rates of 60 and 120 ppm as finely ground triple superphosphate. To leach the soils 1190 ml of distilled water were applied in 13 successive additions of 50 to 200 ml. In contrast to soils from Profile I the rate with which P was leached was rapid and in considerable amount, namely, 94 and 89% of the total P applied to unlimed soil for the 60 and 120 ppm P rates, respectively. Furthermore, 78 and 77% of the P was present in the first leaching after addition of only 70 ml of distilled water. Further leachings contained only 0.5 to 6% of the total P applied (Tables 17, 46 and 47, and Fig. 7).

In limed soils, there was a significant decrease in the amount of P leached, only 75 and 66% was leached after addition of 60 and 120 ppm P, respectively. Approximately 50% of the applied P was present in the first leaching.

Determination of total P in leached limed soils showed that 48 and 73% of the retained P was present in the surface 4 cm soil portion when 60 and 120 ppm P were applied, respectively. The concentration of fixed P decreased consistently with depth in the soil column (Table 44).

Fractionation analysis showed that in soils limed at the rate of 4500 kg/ha and receiving 120 ppm P, approximately 50% of the total retained P was present in the Al-P fraction, 30% as water soluble-P, and the remainder as Fe-P, Ca-P was not measurable (Table 45).

Consistent with previous laboratory analysis, soils from Profile II showed that lime decreased leaching of P, however, the rate at which P was leached from the soil was rather rapid. Most of the fixed P was present in the Al-P fraction.

Experiment I was repeated using fertilized surface soils which were allowed to stand for 48 hr prior to initiation of the leaching process. Phosphorus was not detected in any of the leachings from unlimed or limed soils from Profile I.

The amount of P leached from unlimed and limed soils from Profile II was approximately the same as that which occurred in Experiment I (Table 48). Consequently it was assumed that the distribution of the retained P within the soil column as well as in its inorganic fractions followed the same pattern.

Experiment 2

To study the movement of P within soil Profile I, 300 ml of distilled water were applied in three 100 ml increments. Water additions were then discontinued since percolation through the profile was extremely slow even when mechanical suction was applied and the P concentrations in the leachings were barely detectable.

Low rate of percolation of water in the profile was doubtless due to the clayey nature of this soil, particularly below the 27.5 cm depth layer. The low P concentration in the leachings implied that this soil possessed high P retention capacity. Only 0.55% of the total P added was leached from unlimed soils and 0.68% from limed soil (Tables 18, 19, 50 and 51, and Fig. 8).

The determination of total P present in each of the horizons revealed that 86.5 and 78.8% of it occurred in the surface horizon for unlimed and limed soils, respectively. Total P concentration diminished consistently with depth. It was 8 and 15% in the layer which represented the 15-27.5 cm depth and 4.7 and 5.9% in the 27.5-37.5 cm depth, for the unlimed and limed soils, respectively (Table 54, Fig. 9). All of the retained P was present in the top 3 layers.

Phosphorus fractionation analysis showed that 52% of the fixed P was in the Al-P form, 39% as Fe-P and a very small percentage as water soluble-P, in unlimed soil. In the limed soil 48% of the total retained P was present as Al-P, 34% as Fe-P, and 8% as water soluble-P (Table 56).

For Profile II, 1075 ml of distilled water were applied in 10 successive increments. The amount of P leached was very low, approximately 10% for unlimed soil and 7% from limed soil (Tables 19 and 52, and Fig. 10). These data may indicate that lime increased P retention, even though the P concentration in the leachings increased consistently with the total amount of added water.

Determination of total P in each of the horizons showed the following distribution, from top to bottom: 17, 11, 11, 19, and 42% of the total retained amount in unlimed soil and 28, 8, 11, 19, and 34% in limed soil (Table 54, Fig. 11). The fact that highest percentages were present in the top and in the last two layers of soil may be due to higher organic matter content in the top layer and to higher clay content in the bottom layers.

Table 18.--Phosphorus recovered in leaching from Profile I.

Applied		Recovery	
Lime	P	Total	Percentage
kg/ha	--ug--	--ug--	----%-----
None	None	1.0	--
None	2400	13.3	0.55
12000	2400	16.3	0.68

Table 19.--Phosphorus recovered in leaching from Profile II.

Applied		Recovery	
Lime	P	Total	Percentage
kg/ha	--ug--	--ug--	----%----
None	None	7.2	--
None	3000	301.1	10.1
4500	3000	232.2	7.75

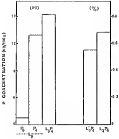

Figure 8.--Phosphorus recovered in leaching from Profile I.

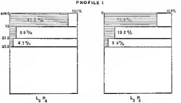

Figure 9.—Total phosphorus retained in Profile I.

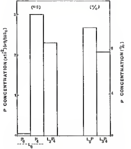

Figure 10.--Phosphorus recovered in leaching from Profile II.

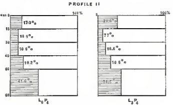

Figure 11.--Total phosphorus retained in Profile II.

When P in the unlimed soil profile was fractionated, 45% of the total retained P was present as Al-P, 32% as Fe-P, and 15% as water soluble-P. In limed soil the distribution was 50% as Al-P, 30% as Fe-P, and 11% as water soluble-P (Table 56). This distribution was consistent in each horizon except for the 60-90 cm depth, where Fe-P predominated over the Al-P fraction, both in limed and unlimed soils. This occurrence may be associated with the increased Fe content of the deeper layers as it also occurred in horizons from Profile I.

Available Soil Phosphorus and Crop Yield Study

Amounts of P extracted from Puletan soils of Profiles I and II varied with the extractant. In general the amount of P extracted increased significantly with the amount of applied P. Amounts of P removed by the different extractants at given P levels were also significantly different.

Bray's solutions (NH_4F + HCl) in both soils, removed the largest amounts of P. Truog's extractant extracted larger amounts of P than NH_4OAc (pH 4.8), at highest rates of applied P. The reverse occurred at low levels of applied P. The amounts of P removed by strong acid extractants were higher than those removed by weak acid solutions with the exception noted above. However, it was possible with all extractants to differentiate between soils high and low in applied P.

Correlation tests between the amount of P removed and pangola-grass yields from three consecutive harvests, as affected by lime and P fertilization, later described, showed that in Profile I, at low rates of applied P, Truog's extractant gave highest correlation with yields, followed by NH_4OAc (pH 4.8), Bray 1, and Bray 2 extractants, respectively. At high rates of applied P, all methods gave negative correlations. The correlation coefficient (r) for Bray 1 was the highest, followed by NH_4OAc (pH 4.8), Bray 2, and Truog, respectively.

In Profile II, at low rates of applied P, the order of correlation coefficients, from high to low, was NH_4OAc (pH 4.8), Truog, Bray 1, and Bray 2, respectively. At high P rates, it was Truog, Bray 1, NH_4OAc (pH 4.8), and Bray 2, respectively.

The data presented in Table 57 and the regression lines depicted in Figs. 12, 13, 14, and 15 showed that while amounts of P removed differed significantly with rates of applied P, forage yields, at the selected lime and P rates, did not vary significantly. Under these conditions, slopes were small with data points scattered more horizontally than vertically. These results indicated the need for further investigation to establish which method or methods are most suitable for correlation of soil P with crop yields after fertilizer P is applied.

Greenhouse Investigations

Exploratory Nutrient and Nutrient Residual Study

Tomato plant response

Oven-dry tomato foliage data expressed in g/pot are presented in Table 30; Figs. 16, 17, 18 and 19. Photographs of selected treatments are shown in Figs. 20 and 21 for surface soils and subsoils.

For Profile I very low yields were produced by both the surface and subsoil, when nutrients were omitted (Treatment 0). Nitrogen and K alone or in combination gave relatively small response. By contrast,

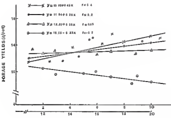

Figure 12.--Relationship between soil available phosphorus and forage yields at low levels of applied phosphorus - Profile I.

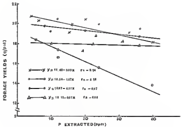

Figure 13.--Relationship between soil available phosphorus and forage yields at high levels of applied phosphorus - Profile I.

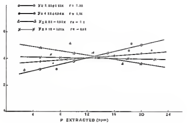

Figure 14.--Relationship between soil available phosphorus and forage yields at low levels of applied phosphorus - Profile 11.

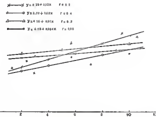

Figure 15.--Relationship between soil available phosphorus and forage yields at high levels of applied phosphorus - Profile II.

Table 20.--Effect of lime and fertilization on tomato plant yields.[1]

Nut.[2]	Lime rates			Lime rates		
	L_0	L_1	L_2	L_0	L_1	L_2
	g/pot					
	PROFILE I					
	Surface Soil			Subsoil		
0	0.05	0.10	0.07	0.04	0.06	0.06
N	0.18	0.23	0.22	0.05	0.11	0.05
P	6.56	11.00	10.00	0.06	0.29	0.37
K	0.06	0.05	0.05	0.05	0.11	0.08
PK	10.01	13.70	12.35	0.15	0.59	0.40
NK	0.12	0.07	0.08	0.15	0.11	0.14
NP	14.15	17.10	0.52	0.18	5.96	3.59
NPK	18.30	24.15	0.27	0.16	13.75	7.63
	PROFILE II					
	Surface Soil			Subsoil		
0	0.29	0.11	0.76	0.09	0.09	0.06
N	0.66	0.19	0.13	0.07	0.15	0.11
P	1.93	6.00	3.50	0.54	0.51	0.44
K	0.64	0.83	0.55	0.21	0.13	0.10
PK	4.50	5.00	4.58	0.30	0.46	0.28
NK	0.40	0.32	0.11	0.35	0.14	0.15
NP	10.40	9.40	16.37	8.00	12.08	7.65
NPK	39.50	32.25	37.00	17.00	21.66	23.75

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	2240
L_2	8960	4480

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[1] Average data for three replicates.

[2] Nutrient application rates given in Table 7.

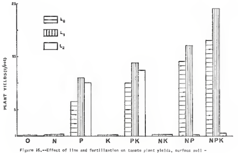

Figure 16.--Effect of lime and fertilization on tomato plant yields, surface soil - Profile I.

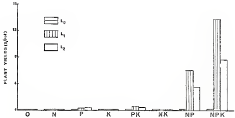

Figure 17.--Effect of lime and fertilization on tomato plant yields, subsoil - Profile I.

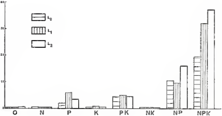

Figure 15.--Effect of lime and fertilization on tomato plant yields, surface soil - Profile 11.

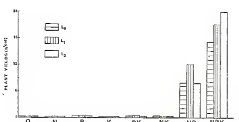

Figure 19.--Effect of lime and fertilization on tomato plant yields, subsoil - Profile II.

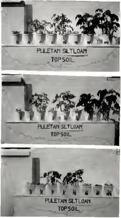

Figure 20.--Effect of lime and fertilization on tomato plant growth - Profile I.

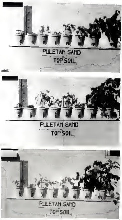

Figure 21.--Effect of lime and fertilization on tomato plant growth - Profile 11.

growth response where P was included was very large, frequently more than 50 times the production without P. Nitrogen and K, each, in combination with P, gave large responses above those obtained with P alone and even higher yields when the 3 elements were combined. This same tendency, though more marked, was noticed in the subsoil where yields, particularly in unlimed soil, were extremely low.

Lime at the rate of 4480 kg/ha significantly increased yields when P was added, either alone or in combination with N and/or K fertilizers. There was an inexplicable marked decrease in yields in the NP and NPK treatments when the topsoil was limed at the rate of 8960 kg/ha. This phenomenon was not observed in subsequent experiments where the same soil and similar treatments were used. Determination of available P, by the Bray I method, in soil samples taken from these two treatments gave similar P values, around 112 ppm, to those in the P or PK treatments. Therefore, it was evident that P fertilizer was not omitted in the NP and NPK treatments.

The small yields produced without P fertilizer regardless of the addition of other nutrients indicated that this element was perhaps the most critical in these soils. It must be applied in adequate quantity if they are to be productive. Soil components also did not mineralize sufficient N to give maximum yields.

Though there was no response to applied K alone or in combination with N, K in the presence of P produced significant yield increases mainly in the surface soil. Other nutrient elements were apparently provided in adequate quantities since no symptoms of deficiency or toxicity were observed in the plants.

Visual observations denoted well grown, healthy, and vigorous plants in pots where P fertilizer was added. Lack of this element produced small, stunted plants manifesting typical P deficiency symptoms, i.e., darker green color than normal with a purplish tinge on the underside of the leaves, and slender stems with purplish tinge close to the bud.

Typical N deficiency symptoms, characterized by pale or yellow color of the leaves, also were present in plants growing in pots lacking this element. Potassium deficiency was evidenced by scorching of the leaf borders which became more pronounced with time.

Nutrient concentrations in the tomato foliage were noticeably increased by fertilization (Table 21). Tomato foliage from the surface soil without P fertilization had P concentrations between 0.01 and 0.09% which are extremely low. When P fertilizer was applied, foliage P concentrations increased to values ranging between 0.2 and 0.3%. Plant P concentrations increased with rate of lime applied, though not in the same proportion, the P treatment alone almost doubled the yield from limed soils, and the increase in P uptake was only approximately 30%.

Potassium concentration in tomato plants was also increased by K fertilization. There may have been an increase in K concentration due to lime application but it was not consistent nor significant. Potassium in combination with N and P produced consistently the highest K concentration regardless of the rate of liming.

Foliage Ca concentrations,in general, were low relative to Mg concentrations where the soil was unlimed regardless of the fertilizer treatment. Calcium concentrations were increased markedly by liming whereas Mg concentrations were not affected. The relation was reversed

Table 21.--Effect of lime and fertilization on nutrient concentrations in tomato plants.

Lime kg/ha	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
		%							
		PROFILE I							
		SURFACE SOIL				SUBSOIL			
None	O	0.06	0.30	0.78	1.13	0.09	0.62	1.17	1.18
	N	0.07	0.45	0.71	1.40	0.05	0.16	0.56	0.72
	P	0.19	0.46	0.62	0.58	0.26	0.84	0.94	0.86
	K	0.07	2.88	0.56	1.46	0.07	1.61	0.99	1.11
	PK	0.14	2.05	0.37	0.37	0.18	2.68	0.49	0.57
	NK	0.09	2.12	0.50	1.22	0.07	0.82	0.61	1.13
	NP	0.16	0.28	0.51	0.56	0.15	0.46	0.94	1.09
	NPK	0.10	1.67	0.44	0.49	0.14	0.81	0.88	1.27
4480	O	0.07	0.64	2.73	1.11	0.08	0.85	4.42	1.08
	N	0.08	0.57	2.50	0.78	0.05	0.40	3.62	0.94
	P	0.29	0.50	1.77	0.42	0.13	1.11	3.70	0.56
	K	0.05	2.16	2.45	1.41	0.06	2.62	3.47	0.91
	PK	0.26	2.00	1.56	0.22	0.10	1.60	2.77	0.37
	NK	0.01	0.56	2.39	0.87	0.06	0.86	3.31	0.91
	NP	0.21	0.34	1.87	0.21	0.14	0.30	2.91	0.85
	NPK	0.14	1.35	1.50	0.34	0.16	1.53	1.76	0.36
8960	O	0.06	0.56	4.10	1.16	0.06	0.79	5.11	1.10
	N	0.05	0.65	3.53	0.49	0.06	0.58	3.77	0.79
	P	0.21	0.48	1.76	0.31	0.07	0.99	3.51	0.42
	K	0.06	2.09	3.27	1.03	0.05	2.19	4.41	1.17
	PK	0.16	2.43	1.78	0.22	0.14	1.79	3.33	0.35
	NK	0.06	1.78	3.88	0.52	0.04	1.11	3.70	0.85
	NP	0.09	2.55	4.22	0.79	0.14	0.40	3.41	0.91
	NPK	0.08	3.15	4.55	0.69	0.10	1.84	2.38	0.42

in limed soils, where Ca concentration was consistently higher than Mg concentration and it increased with rate of liming. Hortenstine and Stall (68) reported a similar effect of lime on Ca concentrations in tomato foliage. They found that Ca concentrations were 0.77%, 1.02, and 1.11% when rates of lime were 500, 2000, and 5000 kg/ha, respectively.

Plant growth on soil components of Profile II was very poor without nutrient additions, particularly of P (Table 20). Phosphorus and lime generally gave large yield increases. Phosphorus in combination with N and K produced the highest yields.

There was little growth response to N and K applied separately or in combination. The appearance of the plants was similar to that for plants growing on soils from Profile I.

A major difference between Profiles I and II was the relatively more severe deficiencies of N and K in soil components from Profile II than from Profile I. Phosphorus alone in the surface soil from Profile I gave yields from approximately 6 to 11 g/pot while in Profile II yields with P alone varied from approximately 2 to 6 g/pot. However, when N and K were combined with P, yields were higher from Profile II than Profile I.

In general, plant nutrient concentrations were significantly increased by fertilization (Table 22). Phosphorus concentrations were generally less than 0.1% without applied P and ranged from 0.1 to 0.3% with P applied.

Potassium concentrations were appreciably increased by K fertilization. Potassium concentrations without applied K were variable but were generally less than 1%. With applied K they were always in

Table 22.--Effect of lime and fertilization on nutrient concentrations in tomato plants.

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		%							
				PROFILE II					
		SURFACE SOIL				SUBSOIL			
None	0	0.06	0.06	0.89	2.38	0.07	1.25	0.65	2.12
	N	0.04	0.68	0.66	1.47	0.14	0.61	0.49	1.64
	P	0.67	1.15	0.70	1.37	0.69	1.51	0.55	1.05
	K	0.05	5.93	0.72	1.52	0.11	5.45	0.30	1.24
	PK	0.30	3.16	0.53	0.56	0.61	3.96	0.34	1.00
	NK	0.03	3.35	0.42	1.17	0.08	3.07	0.40	1.19
	NP	0.67	0.36	0.45	0.65	0.42	0.33	0.17	0.70
	NPK	0.31	2.72	0.38	0.48	0.25	2.03	0.23	0.41
2240	0	0.07	0.80	1.85	1.72	0.10	1.05	2.85	2.75
	N	0.06	0.10	3.23	2.13	0.09	1.00	2.54	2.03
	P	0.34	0.67	1.20	1.07	0.56	1.31	1.78	1.02
	K	0.05	2.47	1.45	1.55	0.14	4.40	1.79	1.22
	PK	0.15	2.72	1.15	0.53	0.50	3.38	0.74	0.51
	NK	0.06	4.20	1.67	1.58	0.07	4.16	1.94	1.60
	NP	0.27	0.39	1.39	0.59	0.37	0.40	1.44	0.63
	NPK	0.11	1.33	1.01	0.37	0.19	1.73	1.12	0.44
4480	0	0.09	0.30	2.00	1.25	0.10	1.02	2.58	1.90
	N	0.05	0.82	2.91	2.10	0.08	0.70	2.51	1.75
	P	0.35	0.50	1.31	0.97	0.72	0.79	1.66	1.12
	K	0.14	3.17	1.21	1.51	0.14	4.11	1.87	1.35
	PK	0.47	2.53	0.96	0.65	0.33	3.09	1.20	0.80
	NK	0.09	3.75	2.42	1.57	0.07	5.05	1.72	1.42
	NP	0.32	0.29	1.95	0.63	0.41	0.21	1.39	0.74
	NPK	0.27	1.07	1.86	0.37	0.29	1.54	1.07	0.42

excess of 1% and frequently as high as 2 or 3%. Calcium and Mg concentrations followed the same pattern described for soils of Profile I, ie that Ca concentration increased with increasing rates of lime while Mg remained almost constant.

Tomato root dry weights and nutrient concentrations are presented in Tables 58, 59, and 60.

Dry weights of roots, both from surface and subsoils of Profile I, showed a linear relationship to oven-dry tomato foliage with the relationships expressed by the equations $y = -0.62 + 6.54\ x$ and $y = -1.52 + 6.41\ x$, in which x = dry weight of roots in g/pot and y = dry weight of the aerial parts in g/pot, for topsoil and subsoil, respectively. Correlation coefficients for the surface soil and subsoil were $r = 0.82$ and $r = 0.94$, respectively. The linear relationships for the surface soil and subsoil from Profile II were expressed by the equations $y = 2.30 + 3.24\ x$ and $y = 3.58 + 5.66\ x$. The correlation coefficients were $r = 0.84$ and $r = 0.97$, respectively.

In general, the effect of lime and fertilization on root production was similar to that for foliage, in that the root proliferation was stimulated by P fertilizer, while N and K showed negligible effects in the absence of P (Figs. 22 and 23).

Nutrient concentrations in tomato roots were also significantly increased by fertilization. Phosphorus, K, Ca, and Mg concentrations, although lower than in the aerial plant parts, followed the same trends.

Pangolagrass response

Pangolagrass was planted in the same pots following the tomato crop to determine the residual effect of applied nutrients. Oven-dry

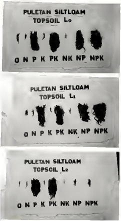

Figure 22.--Effect of lime and fertilization on tomato root growth - Profile I.

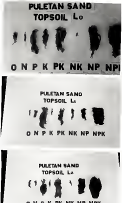

Figure 23.--Effect of lime and fertilization on tomato root growth - Profile II.

forage yields for two consecutive harvests are presented in Table 23. Additional tables showing individual yields for each harvest are presented in the Appendix section (Tables 61 and 62).

Pangolagrass yields from Profile I were low without applied nutrients, particularly P, both for surface and subsoil. Yield differences between the NPK treatment and those lacking P were as high as twenty-fold. The NP and NPK treatments in the surface soil at the highest lime rate also produced very low yields. In general, yields were lower in the 2nd harvest, especially in the absence of P fertilizer. Shortage of this nutrient in these treatments where P was omitted, and of soil N and K, in almost all treatments may have accounted for such decrease in yields. In fact, N and K deficiencies in the plants were evident and common to all treatments. An additional dose, equivalent to the original application, was made to the N and K treatments, respectively, to overcome their shortage in the soil. Additional N and K applications, equivalent to the original quantities, were made to appropriate N and K treatments to overcome soil deficiencies.

Plant K concentration (Table 24), in the presence of K fertilizer, remained constant in both harvests, while noticeable decline was observed in plants from the second harvest in absence of K fertilizer. Plant P concentration showed similar differences as for K, in that it remained quite constant in the presence of P fertilizer, while it declined in the second harvest in absence of P fertilizer. Magnesium concentration in the plant remained without noticeable fluctuation regardless of the time of harvest or rate of liming. Calcium concentration in the plant increased with rate of liming. Presumably, the imbalance between soil Ca and K, particularly after the first harvest, may be responsible for decline in yields in limed soil as compared to unlimed soil.

Table 23.--Effect of lime and fertilization on yields of pangolagrass forage.[1]

Treatment[2]	Lime rates			Lime rates		
	L_0	L_1	L_2	L_0	L_1	L_2
	----------------------g/pot----------------------					
	PROFILE I					
	Surface Soil			Subsoil		
O	0.40	0.80	1.20	0.40	0.90	0.40
N	0.60	0.70	0.30	1.00	0.60	0.60
P	10.50	10.00	4.10	2.40	4.30	2.10
K	1.70	1.30	0.70	1.40	0.70	0.50
PK	11.50	10.70	10.60	2.30	1.80	1.80
NK	1.60	0.20	0.30	1.30	0.90	0.80
NP	11.20	10.10	0.20	5.20	3.70	1.20
NPK	16.20	10.30	0.70	7.20	5.50	2.10
	PROFILE II					
	Surface Soil			Subsoil		
O	2.80	2.10	0.70	0.70	0.30	0.50
N	1.50	0.70	0.60	0.40	0.50	0.70
P	3.20	3.70	1.70	0.70	0.60	0.70
K	1.80	0.60	1.60	0.60	0.40	0.40
PK	2.70	3.20	2.10	0.50	0.70	0.80
NK	1.10	0.40	1.70	0.70	0.50	0.40
NP	3.00	6.70	5.50	2.90	3.10	2.30
NPK	5.80	6.00	2.50	4.50	1.90	2.00

Lime	Profile I	Profile II
	---------kg/ha---------	
L_0	none	none
L_1	4480	2240
L_2	8960	4480

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[1] Average data for two harvests.

[2] Nutrient application rates given in Table 7.

Table 24.--Effect of lime and fertilization on nutrient concentration in pangolagrass forage.[1]

Lime	Treat	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		%							
					PROFILE I				
		SURFACE SOIL				SUBSOIL			
None	0	0.02	1.68	0.19	0.25	0.06	1.53	0.36	0.23
	N	0.04	1.35	0.28	0.25	0.04	1.25	0.29	0.25
	P	0.11	0.34	0.12	0.14	0.12	0.99	0.21	0.22
	K	0.03	1.90	0.16	0.22	0.04	0.71	0.21	0.24
	PK	0.10	1.18	0.11	0.59	0.13	0.74	0.18	0.17
	NK	0.06	1.02	0.09	0.14	0.04	1.71	0.22	0.31
	NP	0.13	0.16	0.14	0.15	0.10	0.78	0.14	0.24
	NPK	0.08	0.61	0.12	0.13	0.12	2.13	0.15	0.22
4480	0	0.03	1.24	0.48	0.15	0.04	1.28	0.45	0.29
	N	0.03	1.28	0.67	0.14	0.05	0.88	0.93	0.30
	P	0.15	0.43	0.19	0.21	0.11	0.90	0.36	0.32
	K	0.03	1.75	1.03	0.24	0.04	1.77	0.53	0.31
	PK	0.09	1.64	1.04	0.27	0.11	1.70	0.39	0.27
	NK	0.04	3.33	2.80	0.29	0.04	1.91	0.51	0.31
	NP	0.12	0.72	0.28	0.28	0.12	0.51	0.21	0.24
	NPK	0.10	0.73	0.30	0.21	0.11	1.10	0.20	0.21
8960	0	0.03	1.49	0.44	0.21	0.04	1.00	0.50	0.31
	N	0.04	1.64	2.03	0.14	0.03	1.04	1.20	0.21
	P	0.07	0.34	0.23	0.28	0.09	0.78	0.44	0.29
	K	0.05	2.24	0.47	0.24	0.04	1.75	0.49	0.24
	PK	0.09	0.67	0.19	0.17	0.06	2.17	0.47	0.27
	NK	0.04	2.05	0.94	0.15	0.04	1.64	0.54	0.21
	NP	0.07	1.72	1.57	0.15	0.09	0.61	0.35	0.32
	NPK	0.07	2.05	0.89	0.17	0.09	1.05	0.30	0.28

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[1] Average data for two harvests.

Forage production from the surface soil and subsoil of Profile II was significantly increased by fertilization, particularly by P (Table 23). In absence of this nutrient, yield response to other fertilizers was small, especially in the subsoil. Difference in yields with time of harvest and with rates of lime were similar and perhaps more noticeable than in soils of Profile I. Explanation for decline in yields given for Profile I may apply identically for soils of Profile II.

Visual observation of plants growing in the greenhouse showed marked differences due to P fertilization. In the absence of this nutrient, plant stolons were as long as 2.5 m compared to approximately 10 cm where P was omitted. Number of stems was another treatment manifestation. In the presence of P, plants produced from five to six stems as contrasted to only one for the poorly developed plants growing without applied P. The small, stunted plants from treatments without P had thin stems and purplish lower internodes, which apparently are typical symptoms of P deficiency in this forage plant. Nitrogen and K deficiencies were also common in almost all treatments. Additional application of N and K fertilizers was required in all N and K treatments.

Plant nutrient concentration followed similar variations as for Profile I (Table 25), particularly in the Ca-K relationship. The sharp decrease in K concentrations, where K fertilizer was omitted, showed the low reserve of native soil K.

Oven-dry pangolagrass root weights responded to fertilization similarly to the tomato. Root proliferation was markedly higher where P was applied. Otherwise, root response followed the same

Table 25. Effect of lime and fertilization on nutrient concentrations in pangolagrass forage.[1]

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		%							
		PROFILE II							
		SURFACE SOIL				SUBSOIL			
None	0	0.04	1.37	0.17	0.29	0.03	1.05	0.26	0.38
	N	0.02	0.66	0.08	0.16	0.03	0.53	0.12	0.17
	P	0.20	0.66	0.15	0.24	0.41	1.35	0.19	0.40
	K	0.05	2.43	0.15	0.33	0.04	3.42	0.34	0.31
	PK	0.20	2.63	0.12	0.18	0.23	2.32	0.13	0.19
	NK	0.04	1.12	0.07	0.12	0.03	1.14	0.15	0.26
	NP	0.21	0.61	0.06	0.12	0.22	0.85	0.12	0.16
	NPK	0.20	2.27	0.12	0.14	0.13	1.45	0.14	0.20
2240	0	0.04	1.57	0.37	0.36	0.04	1.10	0.42	0.37
	N	0.01	0.64	0.19	0.17	0.03	1.42	0.85	0.37
	P	0.43	0.53	0.68	0.30	0.20	0.74	0.26	0.27
	K	0.04	3.14	0.31	0.58	0.04	1.27	0.65	0.31
	PK	0.25	2.56	0.19	0.24	0.21	2.70	0.27	0.24
	NK	0.03	1.32	0.18	0.23	0.06	1.47	1.50	0.39
	NP	0.13	0.40	0.38	0.21	0.11	0.44	0.39	0.23
	NPK	0.15	1.68	0.28	0.19	0.08	1.17	0.29	0.19
4480	0	0.03	1.57	0.31	0.56	0.04	1.32	0.49	0.39
	N	0.01	1.71	0.19	0.16	0.03	1.11	1.02	0.38
	P	0.22	0.86	0.19	0.34	0.17	0.77	0.31	0.28
	K	0.05	2.79	0.22	0.40	0.07	1.52	0.76	0.34
	PK	0.26	2.36	0.27	0.24	0.18	1.17	0.27	0.27
	NK	0.02	2.46	0.16	0.26	0.05	1.53	0.79	0.34
	NP	0.13	0.63	0.09	0.13	0.09	0.47	0.53	0.24
	NPK	0.17	1.68	0.30	0.19	0.05	0.34	0.13	0.10

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[1] Average data for two harvests.

tendencies shown by the forage in regard to dry weights and nutrient concentrations (Tables 63, 64 and 65).

Hairy indigo response

Yields of oven-dry hairy indigo from both profiles were very low (Table 26). The highest yield was 2.55 and the lowest 0.10 g/pot. Yields were increased by applied P, particularly by the complete NPK treatment. In general, yields were higher from the surface soil than from the subsoil of Profile I while the reverse occurred for Profile II. The lime effect was inconsistent in contrast to previous crops, though a slight yield increase occurred at the intermediate lime level.

Forage P concentrations were relatively low compared to values of 0.67% obtained in Florida (150). The average P concentration from Profile I with applied P was approximately 0.20% and about 0.40% from Profile II (Tables 27 and 28). It is possible that the low yields obtained and the relatively low plant heights were due to depletion of nutrients by previous crops. Calculation of total forage P showed that in Profile I, approximately 50 to 69% of the applied P was present in the tomato plant and pangolagrass forage from unlimed soil, while approximately 60 to 76% was present in plants from limed soil at the lower rate. In the surface soil from Profile II, approximately 50% of the applied P was taken up by the tomato plant and pangolagrass forage. The high recovery, even in the case of Profile I surface soil, and depletion of available P by the previous crops may have accounted for low yields of hairy indigo. Other factors such as insufficient N supply and failure of nodulation by indigo plants, may have been responsible for lower yields in the case

Table 26.--Effect of lime and fertilization on hairy indigo forage yields.

Treat.[1]	Lime rates			Lime rates		
	L_0	L_1	L_2	L_0	L_1	L_2
	g/pot					
	PROFILE I					
	SURFACE SOIL			SUBSOIL		
0	0.45	0.75	0.80	0.50	0.20	0.30
N	0.55	0.45	0.40	0.40	0.10	0.10
P	1.65	1.15	1.60	1.10	1.05	0.75
K	0.35	1.05	0.95	0.70	0.10	0.20
PK	2.25	1.05	2.55	1.05	0.40	1.60
NK	0.25	0.15	0.15	0.35	0.10	0.45
NP	1.20	1.60	0.20	0.40	0.55	0.10
NPK	0.95	1.60	0.75	0.70	0.65	0.35
	PROFILE II					
	SURFACE SOIL			SUBSOIL		
0	0.20	0.15	0.40	0.10	0.10	0.10
N	0.10	0.10	0.10	0.10	0.10	0.10
P	0.20	0.45	1.00	2.60	0.30	1.65
K	0.10	0.10	0.10	0.10	0.10	0.10
PK	0.20	0.45	0.35	1.70	0.15	0.15
NK	0.10	0.10	0.10	0.10	0.10	0.10
NP	0.55	1.60	0.30	3.10	1.45	1.85
NPK	0.30	0.20	0.10	1.40	0.90	0.10

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	2240
L_2	8960	4480

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[1] Nutrient application rates given in Table 7

Table 27.--Effect of lime and fertilization on nutrient concentrations in hairy indigo forage.

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha					%				
					PROFILE 1				
		SURFACE SOIL				SUBSOIL			
None	0	0.08	0.74	1.29	1.12	0.08	0.94	0.89	0.38
	N	0.07	0.33	2.15	1.18	0.08	0.55	2.28	1.07
	P	0.29	0.35	1.64	0.89	0.15	1.23	1.64	0.58
	K	0.07	1.48	1.27	1.19	0.07	1.52	1.57	0.41
	PK	0.20	0.32	1.44	0.78	0.14	2.25	1.44	0.53
	NK	0.07	1.36	2.43	1.30	0.07	0.81	1.74	1.19
	NP	0.10	0.37	1.87	0.51	0.16	0.62	1.00	0.46
	NPK	0.16	0.45	1.24	0.58	0.13	0.99	0.93	0.53
4480	0	0.08	0.65	3.28	0.66	0.10	0.87	3.39	0.50
	N	0.06	0.57	4.02	0.70	0.17	0.55	5.27	0.58
	P	0.29	0.47	2.93	0.84	0.22	0.63	3.01	0.58
	K	0.08	1.36	2.65	0.59	0.10	1.30	1.67	0.45
	PK	0.17	0.75	2.30	0.39	0.24	1.80	2.51	0.37
	NK	0.07	1.04	5.26	0.83	0.10	1.15	1.50	0.35
	NP	0.12	0.28	2.89	0.44	0.14	0.58	3.41	0.52
	NPK	0.16	0.23	3.12	0.48	0.15	0.67	3.02	0.51
9960	0	0.09	0.78	3.48	0.33	0.13	0.55	4.61	0.44
	N	0.05	0.42	5.02	0.34	0.10	0.45	4.50	0.40
	P	0.16	0.21	3.12	0.45	0.32	0.44	4.10	0.75
	K	0.08	1.33	3.75	0.40	0.09	0.93	3.93	0.39
	PK	0.25	0.48	3.44	0.58	0.16	1.76	3.12	0.37
	NK	0.07	1.38	7.21	0.41	0.09	0.71	7.63	0.35
	NP	0.12	0.84	4.52	0.36	0.12	0.42	5.71	0.34
	NPK	0.09	1.13	6.09	0.53	0.20	0.58	5.99	0.36

Table 28.--Effect of lime and fertilization on nutrient concentrations in hairy indigo forage.

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
		%							
		PROFILE II							
		SURFACE SOIL				SUBSOIL			
None	0	0.19	0.92	2.07	1.54	0.10	1.10	1.30	1.31
	N	0.02	0.64	1.43	0.66	0.01	0.50	1.20	0.65
	P	0.11	0.92	1.56	1.81	0.51	0.60	1.06	0.94
	K	0.01	0.50	1.25	0.50	0.10	4.45	1.05	0.78
	PK	0.64	5.94	0.73	1.20	0.45	4.00	0.64	0.63
	NK	0.01	0.60	1.30	0.70	0.10	3.00	0.58	0.60
	NP	0.23	0.87	0.82	0.90	0.25	0.37	1.32	0.82
	NPK	0.21	5.34	0.81	0.49	0.12	2.56	1.26	0.50
2240	0	0.13	0.80	2.91	1.88	0.09	1.27	2.37	1.41
	N	0.10	0.60	1.90	1.50	0.10	1.60	4.33	0.70
	P	0.55	0.76	2.32	1.25	0.40	1.19	2.76	1.45
	K	0.18	6.77	2.30	1.15	0.19	7.50	2.85	0.95
	PK	0.43	4.45	0.91	0.61	0.15	5.65	2.34	1.19
	NK	0.10	4.20	2.30	1.10	0.15	5.80	4.65	0.72
	NP	0.21	0.38	3.05	0.67	0.14	0.46	3.36	0.66
	NPK	0.18	4.11	2.30	0.31	0.12	3.68	2.42	0.56
4480	0	0.11	0.86	2.38	1.06	0.11	1.63	2.58	0.91
	N	0.16	0.99	1.93	0.99	0.10	1.50	2.20	0.70
	P	0.47	0.63	1.95	0.96	0.40	0.61	2.03	0.81
	K	0.12	6.89	3.11	1.26	0.14	6.37	3.92	1.00
	PK	0.55	5.83	1.06	0.16	0.39	5.42	2.51	0.95
	NK	0.11	5.50	3.00	0.80	0.16	4.94	4.10	0.73
	NP	0.21	1.16	3.90	0.65	0.10	0.45	3.09	0.44
	NPK	0.20	5.40	3.95	0.65	0.19	3.22	3.21	0.50

of Profile II. Phosphorus deficiency symptoms were general, they were more marked in treatments where P was omitted. Yellowish foliage color resembled N and/or K deficiency.

Micronutrient concentrations in the forage probably were not the cause of low yields. Data obtained in subsequent experiments (Tables 73 and 77) showed that micronutrient concentrations in pangolagrass and pigeon pea were relatively high. These data suggested that micronutrient deficiencies may not be an immediate problem in these soils. On the other hand, the higher P concentrations reported in Florida (150) for hairy indigo, suggested that requirements for this element are higher than could be supplied by the soil after two previous crops were grown without subsequent fertilization with P.

Oven-dry root weights were very low, particularly in the absence of applied P (Table 66). Otherwise, yields followed the same trends shown for previous crops.

Variations in root nutrient concentrations were similar to those in the foliage (Tables 67 and 68). Phosphorus concentrations did not change markedly, and apparently were not affected by lime. Calcium concentrations increased noticeably with increasing lime rates, while Mg concentration remained almost constant.

Lime and Phosphorus Study

Pangolagrass response

Oven-dry forage yields for 3 harvests from Profile I showed that there was a significant response to applied lime and P, particularly at the 4480 kg/ha lime level. At higher lime rates, yields were depressed, but the response to applied P remained (Tables 29, 69, 70, and 71, Figs. 24 and 25).

Table 29.--Effect of lime and phosphorus fertilization on yields of pangolagrass forage.[1]

Applied P	Lime rates L_0	L_1	L_2	L_3
kg/ha	g/pot			
	PROFILE I			
60	11.0	15.9	12.1	11.7
120	13.1	16.6	13.3	10.1
180	15.3	21.0	13.7	14.0
240	16.7	19.6	17.5	18.7
	PROFILE II			
60	5.3	4.2	5.3	5.7
120	3.0	4.4	5.8	7.2
180	4.4	3.7	3.9	6.0
240	4.7	4.3	4.8	6.4

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

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[1] Average yields for three harvests.

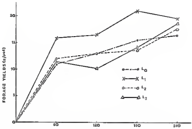

Figure 24.--Effect of lime and phosphorus fertilization on pangolagrass forage yields - Profile 1.

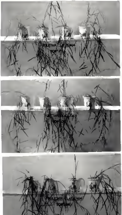

Figure 25.--Effect of lime and phosphorus fertilization on pangolagrass forage growth - Profile 1.

The second harvest was the largest with a slight decrease at the third harvest. Forage P concentrations apparently were not affected by the quantities of lime or applied P, since concentrations were almost uniform in the 3 harvests. They ranged between 0.11 and 0.17%.

The major difference in forage nutrients among the 3 harvests was a sharp decrease in K concentration at the third harvest, from above 2.5% in the first harvest to less than 2% in the third harvest (Table 30). The low native reserve of soil K was emphasized. Decrease in K concentration was accompanied by increase in Ca and Mg concentrations. It is quite possible that fluctuation in the concentrations of these 3 nutrients was a result of an alteration in their relationship in the soil due to rapid depletion of available soil K and consequent relative increase in Ca and Mg concentration. Under these conditions K uptake would be suppressed by the other two elements. Total forage K, for the first two harvests,was in excess of the quantity applied to the soil. This phenomenon was reported by Blue (17) for Puletan loamy fine sand from British Honduras. Furthermore, Gammon and Blue (53) reported the relatively high K requirements of pangolagrass and established a minimum K concentration of 2% in oven-dry forage for optimum growth. Values found for the first 2 harvests were within that range (Table 30).

The yield decrease at the third harvest may also have been caused by shortage of N. In fact, after the second harvest the plants showed marked N and K deficiencies. Additions of these elements, equivalent to 300 and 400 kg/ha, respectively, were applied. Even though, deficiency symptoms disappeared with time, fertilizer application may have been too late to prevent the yield decreases.

Table 30.--Effect of lime and phosphorus fertilization on nutrient concentrations in pangolagrass forage.[1]

Applied Lime	Applied P	P	K	Ca	Mg	P	K	Ca	Mg
-- kg/ha --		%				%			
		PROFILE I				PROFILE II			
None	60	0.10	2.79	0.12	0.16	0.20	2.99	0.15	0.23
	120	0.11	1.96	0.13	0.20	0.22	3.41	0.14	0.19
	180	0.11	1.84	0.13	0.19	0.28	3.55	0.16	0.17
	240	0.13	2.15	0.12	0.16	0.29	3.39	0.19	0.19
L_1	60	0.08	2.23	0.28	0.23	0.18	3.52	0.30	0.22
	120	0.12	2.40	0.28	0.23	0.23	3.47	0.31	0.23
	180	0.13	1.94	0.30	0.28	0.25	3.38	0.29	0.20
	240	0.12	2.13	0.30	0.23	0.26	3.47	0.30	0.21
L_2	60	0.12	2.34	0.35	0.18	0.14	3.44	0.34	0.26
	120	0.12	2.43	0.34	0.22	0.22	3.49	0.36	0.24
	180	0.14	2.44	0.37	0.23	0.22	3.22	0.36	0.20
	240	0.13	2.03	0.37	0.28	0.27	3.61	0.34	0.21
L_3	60	0.10	2.32	0.36	0.22	0.16	3.45	0.34	0.29
	120	0.13	2.49	0.40	0.22	0.21	3.35	0.33	0.24
	180	0.12	2.28	0.35	0.25	0.23	3.36	0.34	0.23
	240	0.14	2.11	0.36	0.24	0.25	3.14	0.34	0.26

Lime	Profile I	Profile II
	kg/ha	
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

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[1] Average data for three harvests.

Decreased yields were probably not due to inadequate micronutrients. Data presented in Table 73 show that concentrations were relatively high for all the elements determined.

Forage yields from Profile II were much lower than those obtained from Profile I (Table 29; Figs. 26 and 27). The first harvest, which was the lowest, was not statistically analyzed, since there was considerable delay in obtaining a uniform plant stand. Subsequent harvests showed significant yield response to lime and P fertilization (Table 72). Highest yields were obtained at highest lime and P levels in the third harvest.

Phosphorus concentration was consistently high, approximately 0.2% regardless of the rate of P applied (Table 30). The fact that yields were consistent among harvests may also be explained in terms of K concentration in the forage, which was high relative to Ca and Mg concentrations. Potassium concentrations were approximately 3% in all harvests, with a slight decrease for the third harvest. On the other hand, forage Ca and Mg concentrations in the first two harvests were constant, but showed an increase for the third harvest. Plants at this stage exhibited foliar symptoms of N and K deficiencies which were overcome by application of both nutrients, equivalent to 300 and 400 kg/ha, respectively. As for soil of Profile I, the time of fertilizer application may not have been sufficiently early to prevent a decrease in forage K concentration.

The results of this experiment showed clearly the imperative need for fertilizer K and possibly also for N to maintain high forage production in Puletan soils, in addition to other nutrients, particularly P. Micronutrient concentrations appeared to be adequate (Table 73).

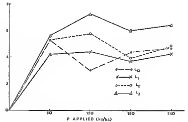

Figure 26.--Effect of lime and phosphorus fertilization on pangolagrass forage yield - Profile II.

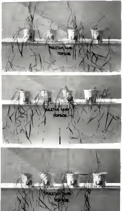

Figure 27.--Effect of lime and phosphorus fertilization on pangolagrass forage growth - Profile II.

Root weights (Table 31) followed the same pattern shown by the forage. For Profile I, root proliferation was highest at the 4480 kg/ha lime level. Weights decreased noticeably with higher lime rates. In Profile II, yields increased with lime and P rates. In both soils, P concentration in the roots was relatively constant regardless of the rate of P applied (Table 74). Calcium concentration increased as lime rates were increased, while Mg concentrations remained relatively constant. In every case, nutrient concentrations were higher in roots and forage from Profile II than from Profile I.

Pigeon pea response

Pigeon pea was grown as the second crop following pangolagrass. Lime and P fertilization of Profile I significantly increased forage yields (Tables 75 and 76). Highest yields were obtained at lime rates of 8960 and 13440 kg/ha. Yields increased consistently with applied P (Table 32).

Even though forage P concentrations showed slight increases at higher rates of lime, they were irregular and inconsistent. Potassium concentrations increased with rates of lime and P while Ca and Mg concentrations decreased noticeably (Table 33). These fluctuations were doubtless due to K addition to the soil prior to the third harvest of the previous pangolagrass crop.

Micronutrient concentrations in the plants were relatively high, however, Zn showed a marked decrease in limed soils, which apparently was not reflected in forage yields (Table 77).

Yields from Profile II (Table 33) were significantly increased by lime and P fertilization but were lower than from Profile I. Yields were highest at the low lime rate.

Table 31.—Effect of lime and phosphorus fertilization on pangolagrass root weights.

Applied P	Lime rates			
	L_0	L_1	L_2	L_3
kg/ha	---------------- g/pot			----------------
	PROFILE I			
60	1.6	2.1	1.2	1.6
120	3.0	1.6	1.3	0.9
180	3.5	2.7	1.4	1.3
240	2.7	2.7	2.0	1.6
	PROFILE II			
60	2.1	1.6	0.9	0.8
120	1.0	0.6	1.2	1.0
160	1.3	1.6	1.4	1.4
240	1.1	1.1	1.5	1.6

Lime	Profile I	Profile II
	-------- kg/ha	--------
L_0	none	none
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

Table 32.--Effect of lime and phosphorus fertilization on pigeon pea forage yields.[1]

Applied P	Lime rates			
	L_0	L_1	L_2	L_3
kg/ha	g/pot			
	PROFILE I			
60	3.1	2.6	2.3	2.7
120	1.6	3.1	3.3	3.2
180	1.7	4.1	4.0	3.6
240	1.8	2.8	3.8	3.8
	PROFILE II			
60	1.5	2.1	1.4	1.6
120	2.3	2.1	1.7	1.6
180	1.4	2.6	1.6	1.9
240	1.2	3.1	1.9	2.3

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

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[1] Average yields for three replicates.

Table 33.--Effect of lime and P fertilization on nutrient concentrations in pigeon pea forage.

Applied Lime	Applied P	P	K	Ca	Mg	P	K	Ca	Mg
		-----	-----	%	-----	-----	-----	%	-----
			PROFILE I				PROFILE II		
None	60	0.09	0.97	0.60	0.25	0.10	4.13	0.50	0.57
	120	0.07	0.70	0.86	0.33	0.22	5.36	0.71	0.54
	180	0.10	0.63	1.34	0.49	0.27	5.76	0.79	0.69
	240	0.08	0.60	1.62	0.53	0.35	5.96	0.82	0.59
L_1	60	0.09	0.97	1.85	0.37	0.08	4.23	1.55	0.42
	120	0.15	0.86	1.82	0.42	0.18	4.73	2.04	0.42
	180	0.12	0.53	1.23	0.35	0.34	4.93	1.82	0.46
	240	0.12	0.77	1.32	0.31	0.28	4.73	2.36	0.57
L_2	60	0.09	1.45	1.42	0.17	0.08	4.26	2.21	0.44
	120	0.13	1.54	1.27	0.18	0.12	4.03	2.10	0.46
	180	0.15	1.16	1.26	0.22	0.20	5.83	2.44	0.47
	240	0.19	0.67	1.28	0.30	0.26	4.36	2.36	0.39
L_3	60	0.07	1.65	1.30	0.10	0.07	3.73	1.97	0.41
	120	0.14	2.06	1.29	0.11	0.12	4.03	1.95	0.39
	180	0.19	1.36	1.25	0.20	0.17	3.90	2.68	0.46
	240	0.17	0.92	1.27	0.24	0.18	3.90	2.37	0.43

Lime	Profile I	Profile II
	-------- kg/ha	--------
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

Forage P concentrations did not show marked differences with rates of applied P. Potassium concentrations were approximately 4.0% and decreased to about 3.5% at the highest lime rate. There was an irregular increase in Ca concentration with lime rates, but Mg was relatively constant. As for Profile 1, the relatively high K concentrations were a consequence of the applications of this element to the soil prior to the third harvest of the previous pangolagrass crop. It is quite possible that such addition may have upset the depressed plant Ca and Mg uptake, which in turn was reflected in decreased yields.

Micronutrient concentrations appeared to be high and probably did not limit yields (Table 77).

Root weights (Table 34) were affected by lime and P fertilization in a similar way as for the forage. Nutrient concentrations showed similar fluctuations as described for the forage (Table 78).

Table 34.--Effect of lime and phosphorus fertilization on pigeon pea root weights.[1]

Applied P	Lime rates			
	L_0	L_1	L_2	L_3
kg/ha	g/pot			
	PROFILE I			
60	1.0	1.0	0.9	1.1
120	0.9	0.9	1.2	1.2
180	0.9	1.3	1.1	1.0
240	0.7	1.0	1.4	1.3
	PROFILE II			
60	0.4	0.4	0.2	0.3
120	0.2	0.4	0.2	0.3
180	0.3	0.3	0.2	0.4
240	0.2	0.4	0.4	0.3

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

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[1] Average weights for three replicates.

APPENDIX

Table 35.--Textural classification of Puletan soils.

Soil	Soil Depth	*Sand						Silt	Clay	Textural Classification
		V.C	C	M	F	V.F	Total			
	- cm -	%								
53	0-15	3.5	14.5	13.0	18.1	12.1	61.2	15.6	23.2	Sandy clay
	15-30	4.4	9.4	9.0	22.0	12.4	57.2	14.2	28.6	" "
53a	0-15	15.7	30.5	6.0	9.9	8.7	70.8	9.4	19.8	Sandy loam
	15-30	17.6	26.4	5.2	9.6	8.0	66.8	10.4	22.8	" "
53d	0-15	1.0	12.4	15.8	32.8	9.2	71.3	15.7	13.0	Sandy loam
	15-30	2.2	28.8	15.6	22.8	8.4	77.8	10.2	12.0	" "
53e	0-15	0.6	6.3	8.8	34.4	3.9	54.0	18.4	27.6	Sandy clay
	15-30	2.2	8.8	7.4	30.2	9.6	58.2	19.0	22.8	" "
53f	0-15	0.1	0.4	0.4	1.0	2.1	4.0	10.4	85.6	Clay
	15-30	0.2	0.3	0.4	0.8	1.0	2.8	2.0	95.2	"

*Abbreviations V.C = very coarse (2.0-1.0 mm), C = coarse (1.0-0.5 mm)
M = medium (0.5-0.25 mm), F = (0.25-0.1 mm)
V.F = very fine (0.1-0.05 mm)
Silt = 0.05-0.002 mm
Clay = <0.002 mm

Table 36.--Actual weights of cylinder samples and calculated pore space.

	Weight basis (actual)					Volume basis (%)			
Depth	Wet wt.	Dry wt.	Wt. water diff.	Bulk density	Particle density	Total pore space	Dry soil	Water	Air
cm	g					%			
				PROFILE I					
0-15	121.1	58.5	62.6	0.85	2.52	66.4	33.6	91.2	0
15-27.5	136.7	98.5	38.2	1.43	2.66	46.2	53.8	55.6	0
27.5-37.5	146.3	105.0	41.3	1.52	2.65	42.6	57.4	60.1	0
37.5-90	143.4	99.5	43.9	1.50	2.71	44.6	55.4	63.9	0
				PROFILE II					
0-15	136.7	101.5	35.2	1.48	2.68	44.8	55.2	51.1	0
15-30	160.1	130.5	29.6	1.90	2.69	29.4	70.6	43.1	0
30-45	165.1	137.0	28.1	1.99	2.69	26.0	74.0	40.9	0
45-60	165.1	138.5	26.6	2.01	2.69	25.3	74.7	38.7	0
60-90	165.1	138.5	26.6	2.00	2.65	24.5	75.5	38.7	0

Table 37.--Porosity characteristics. Capillary and non-capillary pore space. Partition of water.

Depth	Porosity constants			At time of sampling		
	Total p. space	Cap.p. space	Non-cap.p. space	Total water	Water in noncap.p.	Air in non-cap.p.
--- cm ---	----------	----------	---------- Vol.%	----------	----------	----------
PROFILE I						
0-15	66.4	16.7	49.7	91.2	74.5	0
15-27.5	46.2	13.6	32.6	55.6	19.0	0
27.5-37.5	42.6	14.0	28.6	50.1	46.1	0
37.5-90	44.6	46.0	0	63.9	17.3	0
PROFILE II						
0-15	44.8	3.4	41.4	51.1	47.7	0
15-30	29.4	0.9	28.5	43.1	42.2	0
30-45	26.0	5.0	21.0	40.9	35.9	0
45-60	25.3	1.4	23.9	38.7	37.3	0
60-90	24.5	0.3	24.2	38.7	38.5	0

Table 38.--Sticky point and index of texture.

Depth	Wet wt.	Dry wt.	Wt. water diff.	S. Point	Sand	Index of texture
-- cm ---		g		%		
			PROFILE I			
0-15	91.9	72.4	19.5	26.8	35.6	19.7
15-27.5	95.4	82.2	13.2	16.1	33.2	9.5
27.5-37.5	98.5	85.1	13.4	15.6	32.2	9.2
37.5-90	99.7	75.7	24.0	31.7	3.2	31.1
			PROFILE II			
0-15	94.5	80.5	14.0	17.5	75.8	2.3
15-30	114.8	100.8	14.0	13.9	67.2	0.5
30-45	94.0	81.5	12.5	15.4	64.6	2.5
45-60	95.8	84.3	11.5	13.6	64.4	0.7
60-90	113.5	99.8	13.7	13.7	72.8	0.1

Table 39.--Chemical analyses of Puleton soils.

Soil	Depth cm	pH H$_2$O	pH KCl	O.M.	N	C/N	Av. P	Org. P	Exch. Cap.	Exch. Cations Ca	Exch. Cations Mg	Exch. Cations K	Na	Base Sat.	Ratios Ca/Mg	Ratios Mg/K	Ratios Ca+Mg/K
				--- % ---			-- ppm --		--------- meq/100g ---------					%			
53	0-15	5.5	4.5	1.95	0.11	10.3	8.0	20.5	6.84	1.32	0.98	0.19	0.13	38.3	1.35	5.16	12.1
	15-30	5.3	4.7	--	0.05	--	7.2	6.1	5.25	2.52	1.52	0.29	0.44	90.8	1.66	5.24	13.9
53a	0-15	5.1	4.7	1.79	0.08	12.9	7.6	2.8	2.95	0.42	0.23	0.19	0.34	40.0	1.83	1.21	3.4
	15-30	5.8	4.6	0.35	0.06	6.3	7.6	3.7	2.18	0.38	0.17	0.12	0.31	44.9	2.23	1.42	4.6
53d	0-15	5.1	4.2	2.85	0.12	13.7	8.0	4.0	4.42	0.70	0.27	0.17	0.35	33.7	2.59	1.59	5.7
	15-30	5.6	5.0	0.25	0.03	4.7	6.4	2.1	1.41	0.38	0.12	0.08	0.26	59.6	3.17	1.50	6.2
53e	0-15	5.5	4.3	4.39	0.18	14.2	8.0	22.6	9.14	0.96	0.30	0.38	0.56	24.1	3.20	0.78	3.3
	15-30	5.0	4.5	0.38	0.05	4.4	7.2	3.9	3.47	0.32	0.13	0.17	0.61	35.4	2.46	0.76	2.6
53f	0-15	5.0	4.7	5.28	0.30	10.2	7.2	37.7	52.4	3.87	0.81	0.59	4.34	18.3	4.78	1.37	7.9
	15-30	5.2	5.0	0.82	0.07	6.7	3.2	3.7	60.3	5.94	1.49	0.55	0.96	14.8	3.99	2.71	13.5
							Standards for Comparison (0-15 cm)										
High		7.5		7.0	0.35	11.5	52			24.0	6.0	0.55			--	--	--
Medium		6.5		3.5	0.20	10.0	21			12.0	3.0	0.35			4.0	8.0	40.0
Low		5.0		0.7	0.05	8.5	9			4.0	1.0	0.20			--	--	--
											(0-30 cm)						
High		7.5		5.2	0.26	11.5	39			18.0	4.5	0.41			--	--	--
Medium		6.5		2.6	0.15	10.0	16			9.0	2.3	0.26			4.0	8.0	40.0
Low		5.0		0.6	0.04	8.5	6			3.0	0.8	0.15			--	--	--

Table 40.—Chemical analysis of Pulatan soils.

Soil	Depth	Total	Total cations				Total micronutrients				
	cm	P	Ca	Mg	K	Na	Al	Fe	Zn	Cu	Mn
		ppm	%						ppm		
53	0-15	55.4	0.50	0.12	0.15	2.70	4.40	0.51	920	100	500
	15-30	48.5	0.35	0.10	0.10	0.55	3.60	0.48	260	100	110
53c	0-15	35.7	0.17	0.06	0.25	2.00	3.50	0.43	110	100	80
	15-30	27.1	0.27	0.11	0.25	4.30	6.60	0.73	240	100	80
53d	0-15	46.8	0.36	0.06	0.15	0.65	0.60	0.12	180	100	60
	15-30	24.0	0.17	0.08	0.95	1.40	5.00	0.85	140	100	80
53e	0-15	78.8	0.54	0.11	0.25	0.95	2.90	0.31	410	100	40
	15-30	35.7	0.19	0.07	0.20	0.60	2.30	0.29	130	100	60
53f	0-15	124.9	1.20	0.72	0.20	1.15	11.00	3.79	430	100	140
	15-30	22.0	1.62	1.25	0.40	3.85	14.40	3.63	300	100	184

Table 41.--Chemical analysis of Pulatan soils.

Soil	Depth	Total P	Total cations Ca	Mg	K	Na	Total micronutrients Al	Fe	Zn	Cu	Mn
	cm	ppm	---------------------	-----	%	-----	---------------------		------	ppm	------
					PROFILE I						
53c	0-15	71.4	0.15	0.07	1.20	2.35	4.30	0.53	50	100	80
	15-27.5	68.5	0.14	0.04	0.15	0.65	3.00	0.40	90	100	60
	27.5-37.5	32.1	0.25	0.14	1.10	0.85	7.30	1.00	630	100	60
	37.5-90	40.0	0.18	0.18	1.70	0.65	13.70	2.47	250	100	60
					PROFILE II						
	0-15	28.5	0.26	0.05	0.10	0.90	0.70	0.10	50	100	60
	15-30	32.1	0.19	0.02	0.10	0.15	0.50	0.02	137	100	60
	30-45	24.9	0.28	0.06	0.10	0.35	1.00	0.19	190	100	60
	45-60	34.3	0.16	0.04	0.10	0.40	1.40	0.31	120	100	40
	60-90	24.9	0.17	0.05	0.10	2.50	1.80	0.20	490	100	80

Table 42.--Phosphorus recovered in leaching from surface soil - Profile I.

Applied		No. leachings						
Lime	P	1	2	3	4	5	6	Total
kg/ha	-ug--	ug						
None	None	0.8	0.7	0.5	0.8	0.3	0.2	3.3
None	6000	8.0	4.4	8.4	16.0	1.6	9.6	48.0
None	12000	6.4	3.2	8.8	16.0	5.6	8.0	48.0
12000	6000	16.8	5.4	2.5	27.7	16.8	12.0	81.2
12000	12000	17.8	7.7	3.0	28.0	17.6	10.4	84.5

Table 43.--Phosphorus recovered in leaching from surface soil - Profile I.

Applied		No. leachings						
Lime	P	1	2	3	4	5	6	Total
kg/ha	-ug--	%						
None	6000	0.13	0.07	0.14	0.27	0.03	0.16	0.80
None	12000	0.05	0.03	0.07	0.13	0.05	0.07	0.40
12000	6000	0.28	0.09	0.04	0.46	0.28	0.20	1.35
12000	12000	0.15	0.06	0.02	0.23	0.15	0.09	0.70

Table 44.--Total phosphorus concentration in leached surface soils.

Applied		Soil fractions			
Lime	P	1	2	3	Total
kg/ha	- ug -		ug		
		PROFILE I			
None	None	1141.5	853.4	963.8	2958.7
None	6000	4145.3	958.8	309.3	5413.4
None	12000	6444.0	3925.2	728.7	11097.9
12000	6000	4540.6	1029.9	265.6	5836.1
12000	12000	9294.2	1665.4	1029.0	11988.6
		PROFILE II			
4500	6000	1232.7	149.8	78.2	1460.7
4500	12000	2615.7	668.4	317.2	3601.3

Table 45.--Phosphorus fractions in leached surface soils.

Applied			H_2O			
Lime	P	Layers	Sol-P	Al-P	Fe-P	Ca-P
kg/ha	- ug -		---------------	ug	---------------	
				PROFILE I		
None	12000	1	237.2	3034,7	2422,1	77.6
		2	156.2	2544.3	1222.8	--
		3	167.0	661.1	1038.9	--
12000	12000	1	458.5	4347.7	2399.0	15.8
		2	115.8	710.0	805.4	--
		3	91.4	400,1	504.4	--
				PROFILE II		
4500	12000	1	345,1	862,7	385,7	0,1
		2	151.1	393.4	108.2	--
		3	56.0	220.4	30.8	--

Table 46.--Phosphorus recovered in leaching from surface soil-Profile II.

Applied		No. leachings													
Lime	P	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
kg/ha	- ug -	ug													
None	None	17.3	10.1	4.2	3.5	4.0	2.6	5.2	2.0	7.2	3.8	3.2	3.2	11.6	77.9
None	6000	4687.5	363.3	95.0	95.0	46.3	36.3	33.5	46.7	76.0	25.0	57.0	30.0	53.3	5650.9
None	12000	9300.0	381.7	133.0	152.5	77.0	53.0	65.0	79.0	128.0	52.0	101.3	65.0	124.0	10711.5
4500	6000	3150.0	270.0	145.0	133.3	85.0	59.3	72.0	95.3	122.7	68.7	124.0	92.7	110.7	4528.7
4500	12000	5850.0	415.0	227.5	210.0	130.0	96.0	109.5	168.0	186.0	92.0	187.0	146.0	176.0	7993.0

Table 47.--Phosphorus recovered in leaching from surface soil-Profile II.

Applied		No. leachings													
Lime	P	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
kg/ha	-ug-	%													
None	6000	78.1	6.0	1.6	1.6	0.8	0.6	0.6	0.8	1.3	0.4	0.9	0.5	0.9	94.1
None	12000	77.5	3.2	1.1	1.3	0.6	0.4	0.5	0.6	1.1	0.4	0.8	0.5	1.0	89.0
4500	6000	52.5	4.5	2.4	2.2	1.4	0.9	1.2	1.6	2.0	1.1	2.1	1.5	1.8	75.2
4500	12000	48.7	3.4	1.9	1.7	1.1	0.8	0.9	1.4	1.5	0.8	1.5	1.2	1.5	66.4

Table 48.--Phosphorus recovered in leaching from surface soil after standing 48 hr - Profile II.

Applied		No. leachings												
Lime	P	1	2	3	4	5	6	7	8	9	10	11	12	Total
kg/ha	-ug-	ug												
None	6000	4500.0	240.0	120.0	160.0	155.0	90.0	96.0	54.0	8.0	22.0	106.0	96.0	5647.0
None	12000	7500.0	340.0	205.0	145.0	215.0	136.0	192.0	80.0	40.0	45.0	140.0	152.0	9190.0
4500	6000	2250.0	265.0	125.0	112.5	182.5	128.0	152.0	96.0	36.0	58.0	160.0	148.0	3713.0
4500	12000	4500.0	460.0	250.0	250.0	315.0	200.0	200.0	100.0	84.0	82.0	204.0	220.0	6865.0

Table 49.--Phosphorus recovered in leaching from surface soil after standing 48 hr - Profile II.

Applied		No. leachings												
Lime	P	1	2	3	4	5	6	7	8	9	10	11	12	Total
kg/ha	- ug -	%												
None	6000	75.0	4.0	2.0	2.7	2.6	1.5	1.6	0.9	0.1	0.4	1.7	1.6	94.1
None	12000	62.5	2.8	1.7	1.2	1.8	1.1	1.6	0.7	0.3	0.4	1.2	1.3	76.6
4500	6000	37.5	4.4	2.1	1.9	3.0	2.1	2.1	1.6	0.6	0.9	2.6	2.5	61.9
4500	12000	37.5	3.8	2.1	2.1	2.6	1.7	1.7	0.8	0.7	0.7	1.7	1.8	57.2

Table 50.--Phosphorus recovered in leaching from Profile 1.

Applied		No. leachings			
Lime	P	1	2	3	Total
kg/ha	- ug -	ug			
None	None	--	0.2	0.8	1.0
None	2400	--	5.3	8.0	13.3
12000	2400	1.7	6.4	8.2	16.3

Table 51.--Phosphorus recovered in leaching from Profile 1.

Applied		No. leachings			
Lime	P	1	2	3	Total
kg/ha	--ug--	%			
None	2400	--	0.22	0.33	0.55
12000	2400	0.07	0.27	0.34	0.68

Table 52.--Phosphorus recovered in leaching from Profile II.

Applied		No. leachings										
Lime	P	1	2	3	4	5	6	7	8	9	10	Total
kg/ha	-μg-	μg										
None	None	--	--	--	--	--	2.4	0.8	1.6	--	2.4	7.2
None	3000	3.6	6.0	7.6	37.6	34.3	44.3	38.0	40.7	58.7	40.3	303.1
4500	3000	8.6	3.7	5.3	22.0	25.7	35.3	35.3	30.0	36.3	38.0	232.2

Table 53.--Phosphorus recovered in leaching in Profile II.

Applied		No. leachings										
Lime	P	1	2	3	4	5	6	7	8	9	10	Total
kg/ha	-μg-	%										
None	3000	0.12	0.20	0.25	1.25	1.14	1.48	1.27	1.36	1.69	1.34	10.10
4500	3000	0.02	0.12	0.18	0.73	0.86	1.18	1.18	1.00	1.21	1.27	7.75

Table 54.--Total phosphorus concentration in leached soils.

Applied		Depth Layers (cm)				
Lime	P	0-15	15-27.5	27.5-37.5	37.5-90	Total
kg/ha	-ug-	ug				
				PROFILE I		
None	2400	1972	210	112	--	2294
12000	2400	1762	278	149	--	2289

Table 55.--Total phosphorus concentration in leached soils.

Applied		Depth Layers (cm)					
Lime	P	0-15	15-30	30-45	45-60	60-90	Total
kg/ha	-ug-	ug					
				PROFILE II			
None	3000	456	288	288	504	1094.4	2630.4
4500	3000	776	208	288	504	934.0	2710.0

Table 56.--Phosphorus fractions in leached soils.

Applied			Lr.Depth	H_2O			
Lime	P	Layers	cm	Sol-P	Al-P	Fe-P	Ca-P
-- kg/ha-ug-			----------------	ug	----------------	----------------	----------------
				PROFILE I			
None	2400	1	15	130.0	1050.0	822.0	1.0
		2	27.5	50.0	125.0	40.0	--
		3	37.5	27.5	20.0	50.0	--
12000	2400	1	15	135.0	975.0		
		2	27.5	37.0	105.0	130.0	--
		3	37.5	10.0	40.0	93.0	--
				PROFILE II			
None	3000	1	15	104.0	220.0	128.9	3.2
		2	30	22.0	200.0	54.8	--
		3	45	18.0	150.0	110.0	
		4	60	94.0	230.0	250.6	--
		5	90	208.0	400.0	310.0	
4500	3000	1	15	185.0	375.0	126.5	20.0
		2	30	20.0	150.0	29.0	--
		3	45	20.0	170.0	80.0	--
		4	60.0	32.0	230.0	246.0	--
		5	90	50.0	450.0	352.0	

Table 57.--Amounts of phosphorus removed from Puletan soils by different extractants.

Applied Lime	Applied P	Yield	Truog	NH_4OAc pH 4.8	Bray 1	Bray 2
-- kg/ha --		- g/pot -	ppm			
				PROFILE I		
None	60	11.2	2.0	3.5	13.3	23.1
	60	11.6	7.2	5.5	17.5	23.8
	60	10.3	6.0	4.7	16.8	23.8
	240	17.2	10.0	6.5	49.0	64.7
	240	15.9	16.8	9.7	63.0	77.0
	240	17.1	12.0	8.5	56.0	73.5
4480	60	15.9	7.2	5.7	16.1	23.1
	60	16.1	6.0	4.5	14.0	19.6
	60	15.9	6.0	5.5	16.1	22.4
	240	19.2	24.0	8.7	61.2	82.2
	240	20.0	20.0	11.0	59.5	78.7
	240	19.7	22.0	18.8	61.2	82.2
8960	60	12.3	3.2	4.7	12.6	20.3
	60	13.2	2.0	7.2	11.2	18.2
	60	11.0	2.0	7.8	13.3	20.3
	240	16.9	40.0	13.0	66.5	94.5
	240	18.3	30.0	10.0	47.2	75.2
	240	18.4	30.0	6.2	47.2	68.2
				PROFILE II		
None	60	5.3	6.0	12.5	14.7	19.6
	60	5.1	6.4	13.8	16.1	18.2
	60	5.5	6.0	14.5	16.8	17.5
	240	4.7	65.0	38.7	94.5	106.7
	240	5.1	65.0	27.5	96.2	92.7
	240	4.4	68.0	42.5	96.2	105.0
1680	60	4.8	7.2	10.5	18.9	20.3
	60	4.5	8.0	7.0	14.7	19.6
	60	3.5	6.8	9.5	19.6	19.6
	240	4.7	60.0	40.0	99.7	99.7
	240	4.8	62.0	43.7	96.2	89.2
	240	3.6	40.0	26.2	71.7	82.2
3360	60	4.7	14.0	10.0	18.9	21.8
	60	5.0	10.0	10.0	16.1	20.3
	60	6.2	11.0	9.5	18.9	21.0
	240	4.9	60.0	35.0	80.5	77.8
	240	5.1	65.0	36.2	80.5	92.7
	240	4.4	72.0	45.0	87.5	98.0

Table 58.--Effect of lime and fertilization on tomato root weights.

Treat.[1]	Lime (kg/ha)			Lime (kg/ha)		
	L_0	L_1	L_2	L_0	L_1	L_2
	g/pot					
	PROFILE I					
	Surface Soil			Subsoil		
0	0.20	0.30	0.30	0.30	0.30	0.30
N	0.30	0.20	0.30	0.30	0.30	0.20
P	1.30	1.70	2.10	0.40	0.40	0.40
K	0.30	0.20	0.20	0.40	0.20	0.30
PK	2.30	2.00	2.20	0.40	0.30	0.40
NK	0.20	0.20	0.20	0.30	0.20	0.20
NP	1.30	2.00	0.30	0.40	0.70	0.50
NPK	2.30	2.90	0.30	1.50	2.20	1.60
	PROFILE II					
	Surface Soil			Subsoil		
0	0.10	0.10	0.20	0.10	0.10	0.10
N	0.10	0.20	0.10	0.10	0.20	0.20
P	1.40	1.70	1.30	0.10	0.40	0.20
K	0.20	0.20	0.10	0.10	0.20	0.10
PK	0.50	0.40	1.30	0.20	0.30	0.30
NK	0.60	0.20	0.10	0.10	0.20	0.10
NP	0.80	0.40	0.90	0.60	2.50	1.40
NPK	3.00	4.20	12.80	1.90	3.90	4.60

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	2240
L_2	8960	4480

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[1] Nutrient application rates given in Table 7.

Table 59.--Effect of lime and fertilization on nutrient concentration in tomato roots.

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		-----------	-----------	%	-----------	-----------	-----------	-----------	-----------
					PROFILE 1				
		Surface Soil				Subsoil			
None	0	0.04	0.11	0.95	0.19	0.02	0.16	1.39	0.21
	N	0.04	0.17	1.21	0.16	0.02	0.17	1.50	0.10
	P	0.13	0.15	0.70	0.13	0.06	0.17	1.26	1.61
	K	0.07	0.60	1.49	0.22	0.03	0.52	1.05	0.21
	PK	0.05	0.25	0.55	0.15	0.01	0.61	1.02	0.18
	NK	0.06	1.31	1.64	0.66	0.01	0.75	1.00	0.18
	NP	0.11	0.15	0.45	0.13	0.01	0.94	1.03	0.19
	NPK	0.09	0.34	0.50	0.17	0.04	0.62	0.80	0.20
4480	0	0.04	0.19	1.94	0.17	0.01	0.14	1.47	0.25
	N	0.05	0.10	1.29	0.15	0.01	0.15	2.70	0.22
	P	0.13	0.16	1.05	0.17	0.02	0.18	1.28	0.16
	K	0.04	0.69	2.59	0.26	0.01	0.81	2.02	0.40
	PK	0.13	0.28	1.97	0.18	0.05	0.37	1.45	0.16
	NK	0.03	0.38	1.01	0.19	0.02	0.40	1.50	0.17
	NP	0.12	0.15	1.47	0.19	0.09	0.15	1.97	0.20
	NPK	0.07	0.29	1.29	0.27	0.05	0.27	1.81	0.21
8960	0	0.03	0.17	3.19	0.33	0.01	0.33	2.25	0.12
	N	0.04	0.17	2.08	0.42	0.02	0.57	3.59	0.29
	P	0.13	0.20	1.70	0.15	0.02	0.33	1.57	0.16
	K	0.02	0.48	1.50	0.18	0.02	0.35	1.50	0.16
	PK	0.16	0.29	2.36	0.17	0.03	0.40	2.07	0.18
	NK	0.03	0.40	0.75	0.10	0.03	0.85	2.19	1.35
	NP	0.14	0.11	3.39	0.07	0.06	0.13	2.37	0.03
	NPK	0.12	0.60	3.47	0.18	0.04	0.30	2.19	0.19

Table 60.--Effect of lime and fertilization on nutrient concentration in tomato roots.

Lime kg/ha	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
		%							
		PROFILE II							
		Surface Soil				Subsoil			
None	0	0.09	0.49	1.21	0.43	0.07	0.22	1.12	0.22
	N	0.06	0.25	0.92	0.12	0.17	4.10	5.14	0.68
	P	0.61	0.34	0.64	0.68	0.27	0.28	0.81	1.82
	K	0.14	0.13	0.80	0.24	0.08	0.77	0.96	0.19
	PK	0.30	0.09	0.99	0.69	0.34	0.33	1.22	0.22
	NK	0.07	0.21	2.31	0.22	0.10	2.32	0.97	0.39
	NP	0.54	0.11	0.84	0.22	0.33	0.12	0.98	0.24
	NPK	0.26	0.23	0.52	0.19	0.21	0.11	0.58	0.19
2240	0	0.06	0.31	0.23	0.23	0.13	0.69	1.44	0.23
	N	0.10	0.24	1.83	0.18	0.17	0.29	3.13	0.20
	P	0.67	0.14	1.16	0.70	0.39	0.26	1.68	0.26
	K	0.15	4.27	1.15	1.08	0.15	0.32	2.21	0.25
	PK	0.70	0.40	1.43	0.47	0.16	0.37	0.78	0.15
	NK	0.09	0.14	0.21	0.30	0.13	0.22	1.68	0.22
	NP	0.38	0.15	1.18	0.21	0.25	0.15	1.29	0.35
	NPK	0.30	0.14	1.56	0.30	0.15	0.11	1.80	0.22
4480	0	0.13	0.44	1.96	0.55	0.08	0.34	1.83	0.17
	N	0.06	0.49	2.95	1.14	0.09	0.22	2.09	0.22
	P	0.50	0.15	1.40	0.41	0.16	0.39	1.27	0.21
	K	0.10	2.94	1.47	1.09	0.06	0.51	1.75	0.16
	PK	0.87	0.53	1.76	0.64	0.13	0.20	0.98	0.15
	NK	0.17	1.23	2.48	0.61	0.03	1.40	5.24	0.35
	NP	0.58	0.13	1.53	0.30	0.18	0.11	1.67	0.24
	NPK	0.33	0.34	1.49	0.46	0.13	0.14	1.35	0.24

Table 61 --Effect of lime and fertilization on pangolagrass forage yields.[1]

Treat.[2]	1st harvest L_0	1st harvest L_1	1st harvest L_2	2nd harvest L_0	2nd harvest L_1	2nd harvest L_2
	g/pot					
			PROFILE I			
			Surface Soil			
0	1.1	0.7	0.8	0.3	0.1	0.4
N	0.5	0.6	0.2	0.1	0.1	0.1
P	6.2	5.1	2.0	4.3	4.9	2.1
K	0.9	0.5	0.3	0.8	0.8	0.4
PK	7.0	4.6	3.5	4.5	3.4	7.1
NK	1.5	0.1	0.2	0.1	0.1	0.1
NP	5.2	4.2	0.1	6.0	5.2	0.1
NPK	9.8	4.2	0.2	6.4	6.2	0.5
			Subsoil			
0	0.3	0.7	0.2	0.1	0.2	0.2
N	0.6	0.4	0.5	0.4	0.1	0.1
P	1.6	3.9	1.2	0.8	0.4	0.9
K	0.8	0.5	0.2	0.6	0.1	0.3
PK	1.7	1.4	1.2	0.6	0.4	0.6
NK	0.9	0.8	0.4	0.4	0.1	0.4
NP	2.6	1.1	1.0	2.6	2.6	0.2
NPK	3.6	3.4	1.0	3.6	2.1	1.1

	Lime rates --kg/ha--
L_0	none
L_1	4480
L_2	8960

---

[1] Average data for three replicates.

[2] Nutrient application rates given in Table 7.

Table 62.--Effect of lime and fertilization on pangolagrass forage yields.[1]

Treat.[1]	1st harvest L_0	1st harvest L_1	1st harvest L_2	2nd harvest L_0	2nd harvest L_1	2nd harvest L_2
	-----------	-----------	g/pot	-----------	-----------	-----------
			PROFILE II			
			Surface Soil			
0	0.5	0.5	0.3	1.2	1.6	0.4
N	1.4	0.6	0.5	0.1	0.1	0.1
P	2.4	2.4	0.6	0.8	1.3	0.7
K	0.7	0.4	0.8	1.1	0.2	0.8
PK	1.6	2.0	1.5	1.1	1.3	0.6
NK	1.0	0.3	1.1	0.1	0.1	0.6
NP	3.0	4.3	5.4	0.1	2.4	0.1
NPK	2.2	3.3	2.3	3.6	3.1	0.2
			Subsoil			
0	0.5	0.2	0.4	0.1	0.1	0.1
N	0.3	0.4	0.6	0.1	0.1	0.1
P	0.5	0.6	0.6	0.1	0.1	0.1
K	0.5	0.3	0.3	0.1	0.1	0.1
PK	0.4	0.6	0.7	0.1	0.1	0.1
NK	0.6	0.4	0.3	0.1	0.1	0.1
NP	2.8	2.1	2.1	0.1	0.9	0.2
NPK	2.7	1.6	2.1	1.7	0.3	0.1

Lime rates --kg/ha---	
L_0	none
L_1	2240
L_2	4480

---

[1] Average data for three replicates.

[2] Nutrient application rates given in Table 7.

Table 63.--Effect of lime and fertilization on pangolagrass roots weights.

	Lime rates			Lime rates		
Treat.[1]	L_0	L_1	L_2	L_0	L_1	L_2
	g/pot					
	PROFILE I					
	Surface Soil			Subsoil		
0	0.40	0.30	0.50	0.20	0.20	0.20
N	0.40	0.10	0.10	0.10	0.10	0.20
P	3.10	0.70	0.80	1.00	0.20	0.50
K	1.00	0.20	0.10	0.90	0.10	0.10
PK	2.60	2.20	1.40	0.50	0.30	0.70
NK	0.30	0.30	0.20	0.40	0.60	0.30
NP	2.30	0.50	0.10	0.80	0.30	0.20
NPK	1.60	0.50	0.30	1.50	0.40	0.60
	PROFILE II					
	Surface Soil			Subsoil		
0	1.20	1.00	1.10	0.90	0.20	0.20
N	0.60	0.50	0.20	0.20	0.10	0.60
P	2.20	1.30	0.80	0.60	0.20	0.80
K	0.60	0.40	0.70	0.30	0.30	0.20
PK	2.40	1.30	1.80	0.30	0.20	0.60
NK	0.30	0.20	0.30	0.40	0.30	0.30
NP	0.30	1.20	0.70	1.00	0.70	0.50
NPK	3.90	2.10	0.30	1.00	0.90	0.40

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	2240
L_2	8960	4480

---

[1] Nutrient application rates given in Table 7.

Table 64.--Effect of lime and fertilization on nutrient concentrations in pangolagrass roots.

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		-----------	-----------	-----------	%	-----------	-----------	-----------	-----------
					PROFILE I				
		Surface Soil				Subsoil			
None	0	0.02	0.22	0.30	0.09	0.01	0.20	0.16	0.07
	N	0.03	0.22	0.25	0.13	0.01	0.16	0.17	0.11
	P	0.06	0.23	0.23	0.10	0.05	0.37	0.13	0.06
	K	0.03	0.42	0.23	0.10	0.01	0.41	0.12	0.07
	PK	0.05	0.20	0.18	0.07	0.05	0.44	0.25	0.09
	NK	0.08	0.23	0.26	0.16	0.02	0.31	0.30	0.13
	NP	0.04	0.13	0.19	0.08	0.04	0.67	0.18	0.15
	NPK	0.04	0.12	0.19	0.08	0.03	0.49	0.11	0.08
4480	0	0.01	0.20	0.42	0.11	0.02	0.21	0.34	0.10
	N	0.01	0.10	0.52	0.12	0.01	0.27	0.57	0.13
	P	0.09	0.17	0.31	0.13	0.04	0.32	0.48	0.14
	K	0.01	0.26	0.28	0.10	0.03	0.42	0.46	0.14
	PK	0.05	0.27	0.29	0.10	0.04	0.30	0.43	0.13
	NK	0.12	0.18	1.39	0.17	0.02	0.29	0.46	0.12
	NP	0.05	0.77	0.41	0.13	0.04	0.24	0.42	0.14
	NPK	0.05	0.16	0.41	0.13	0.07	0.24	0.37	0.15
8960	0	0.04	0.29	0.59	0.09	0.03	0.33	0.83	0.11
	N	0.12	0.48	1.20	0.11	0.03	0.25	0.56	0.07
	P	0.04	0.14	0.38	0.11	0.05	0.19	0.26	0.07
	K	0.03	0.21	0.73	0.14	0.01	0.49	0.35	0.11
	PK	0.08	0.13	0.41	0.10	0.03	0.38	0.29	0.08
	NK	0.02	0.26	2.46	0.09	0.01	0.42	0.44	0.10
	NP	0.05	0.10	0.73	0.10	0.04	0.20	0.94	0.09
	NPK	0.04	0.53	0.86	0.13	0.05	0.27	0.59	0.10

Table 65.--Effect of lime and fertilization on nutrient concentrations in pangolagrass roots.

Lime	Treat.	P	K	Ca	Mg	P	K	Ca	Mg
-- kg/ha --					%				
					PROFILE II				
			Surface Soil				Subsoil		
None	0	0.03	0.17	0.27	0.17	0.03	0.27	0.21	0.17
	N	0.05	0.03	0.29	0.08	0.04	0.05	0.29	0.16
	P	0.13	0.21	0.23	0.19	0.07	0.22	0.17	0.16
	K	0.04	1.29	0.32	0.22	0.02	0.35	0.17	0.14
	PK	0.07	1.22	0.21	0.15	0.06	0.49	0.22	0.17
	NK	0.04	0.21	0.28	1.05	0.05	0.21	0.25	0.17
	NP	0.01	0.06	0.37	0.14	0.04	0.08	0.21	0.11
	NPK	0.05	0.77	0.25	0.11	0.03	0.35	0.34	0.14
2240	0	0.03	0.37	0.37	0.20	0.04	0.18	0.76	0.13
	N	0.07	0.08	0.92	0.17	0.06	0.10	0.93	0.15
	P	0.09	0.07	0.29	0.15	0.10	0.19	0.33	0.14
	K	0.02	0.81	0.28	0.15	0.03	1.19	0.42	0.26
	PK	0.11	1.17	0.29	0.18	0.04	0.50	0.39	0.14
	NK	0.06	0.26	0.93	0.11	0.02	0.58	0.76	0.17
	NP	0.09	0.10	0.61	0.17	0.06	0.11	0.67	0.16
	NPK	0.07	0.59	0.59	0.12	0.05	0.36	0.64	0.13
4480	0	0.03	0.13	0.38	0.17	0.02	0.22	0.27	0.12
	N	0.10	0.10	1.22	0.17	0.02	0.17	0.76	0.17
	P	0.13	0.16	0.43	0.18	0.08	0.19	0.33	0.14
	K	0.02	0.48	0.35	0.18	0.02	0.84	0.59	0.14
	PK	0.08	0.73	0.26	0.14	0.08	0.69	0.38	0.14
	NK	0.02	0.41	0.91	0.36	0.03	0.90	0.81	0.14
	NP	0.07	0.09	0.74	0.11	0.05	0.13	0.61	0.13
	NPK	0.07	0.35	0.71	0.10	0.08	0.19	0.69	0.08

Table 66.--Effect of lime and fertilization on hairy indigo root weights.

Treat.[1]	Lime rates			Lime rates		
	L_0	L_1	L_2	L_0	L_1	L_2
	g/pot					
	PROFILE I					
	Surface Soil			Subsoil		
0	0.10	0.10	0.10	0.10	---	---
N	0.03	0.10	0.01	0.03	---	---
P	0.20	0.30	0.30	0.20	0.20	0.10
K	0.10	0.20	0.10	0.10	---	---
PK	0.80	0.40	1.80	0.10	0.05	0.10
NK	---	0.05	---	---	---	---
NP	0.20	0.90	0.10	0.09	0.05	0.08
NPK	0.30	1.00	0.10	0.09	0.09	0.01
	PROFILE II					
	Surface Soil			Subsoil		
0	0.09	0.08	0.10	0.01	---	---
N	0.05	---	---	---	---	0.01
P	0.08	0.20	0.20	0.10	0.05	0.09
K	---	---	0.05	---	---	---
PK	0.10	0.30	0.10	0.10	0.10	0.09
NK	---	---	---	---	---	0.01
NP	0.09	0.20	0.10	0.09	0.20	0.10
NPK	0.10	0.08	---	0.30	0.10	0.01

Lime	Profile I	Profile II
	kg/ha	
L_0	none	none
L_1	4480	2240
L_2	8960	4480

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[1] Nutrient application rates given in Table 7.

Table 67.--Effect of lime and fertilization on nutrient concentrations in hairy indigo roots.

Lime	Treat.[1]	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		-------------------			%	-------------------			
					PROFILE I				
		Surface Soil				Subsoil			
None	0	0.03	0.40	0.42	0.17	0.04	0.18	0.41	0.13
	N	---	---	---	---	---	---	---	---
	P	0.09	0.48	0.36	0.15	0.08	0.44	0.33	0.14
	K	0.01	0.31	0.44	0.15	0.01	0.30	0.75	0.17
	PK	0.09	0.19	0.36	0.12	0.07	0.26	0.39	0.12
	NK	---	---	---	---	---	---	---	---
	NP	0.05	0.26	0.38	0.10	0.05	0.57	0.32	0.14
	NPK	0.05	0.34	0.39	0.10	0.04	0.27	0.61	0.13
4480	0	0.03	0.32	0.69	0.19	---	---	---	---
	N	0.01	0.27	1.15	0.20	---	---	---	---
	P	0.07	0.26	0.49	0.12	0.14	0.20	0.64	0.13
	K	0.06	0.34	0.72	0.15	---	---	---	---
	PK	0.07	0.22	0.66	0.13	0.12	0.12	0.62	0.15
	NK	---	---	---	---	---	---	---	---
	NPK	0.07	0.26	0.51	0.11	0.15	0.19	1.27	0.15
8960	0	0.05	0.33	1.44	0.15	---	---	---	---
	N	---	---	---	---	---	---	---	---
	P	0.11	0.35	0.77	0.13	0.15	0.13	1.04	0.17
	K	0.05	0.11	1.04	0.16	---	---	---	---
	PK	0.11	0.24	0.83	0.15	0.12	0.14	0.93	0.18
	NK	---	---	---	---	---	---	---	---
	NPK	0.03	0.32	1.03	0.16	---	---	---	---

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[1] Nutrient application rates given in Table 7.

Table 68.--Effect of lime and fertilization on nutrient concentrations in hairy indigo roots.

Lime	Treat.[1]	P	K	Ca	Mg	P	K	Ca	Mg
kg/ha		%							
		PROFILE II							
		Surface Soil				Subsoil			
None	0	0.01	0.38	0.61	0.14	---	---	---	---
	N	---	---	---	---	---	---	---	---
	P	0.10	0.19	0.62	0.29	0.21	0.24	0.32	0.23
	K	---	---	---	---	---	---	---	---
	PK	0.03	0.14	0.90	0.14	0.20	0.43	0.31	0.26
	NK	---	---	---	---	---	---	---	---
	NP	0.03	0.15	0.77	0.29	0.06	0.05	0.28	0.12
	NPK	0.02	0.32	0.72	0.16	0.10	0.19	0.48	0.14
2240	0	0.10	0.53	0.67	0.27	---	---	---	---
	N	---	---	---	---	---	---	---	---
	P	0.18	0.08	0.60	0.26	0.10	0.41	0.93	0.31
	K	---	---	---	---	---	---	---	---
	PK	0.18	0.37	0.77	0.19	0.06	0.32	0.71	0.24
	NK	---	---	---	---	---	---	---	---
	NP	0.15	0.06	0.87	0.15	0.08	0.08	0.60	0.18
	NPK	0.09	0.72	1.62	0.36	0.07	0.12	0.80	0.15
4480	0	0.01	0.21	1.10	0.26	---	---	---	---
	N	---	---	---	---	---	---	---	---
	P	0.24	0.09	0.78	0.31	0.21	0.17	0.44	0.26
	K	---	---	---	---	---	---	---	---
	PK	0.12	0.13	0.87	0.20	0.11	0.27	0.88	0.27
	NK	---	---	---	---	---	---	---	---
	NP	0.13	0.26	1.35	0.13	0.09	0.09	0.74	0.19
	NPK	---	---	---	---	---	---	---	---

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[1] Nutrient application rates given in Table 7.

Table 69.--Effect of lime and phosphorus fertilization on pangolagrass forage yields.[1]

P	1st harvest				2nd harvest				3rd harvest			
	L_0	L_1	L_2	L_3	L_0	L_1	L_2	L_3	L_0	L_1	L_2	L_3
kg/ha	g/pot											
	PROFILE 1											
60	3.7	4.5	3.8	3.5	4.0	6.7	4.2	3.8	3.1	4.7	4.0	4.4
120	3.5	5.0	4.1	3.1	7.2	7.1	3.8	3.9	3.3	4.4	4.5	3.1
180	2.8	5.6	4.3	3.7	8.3	10.3	3.8	6.3	3.5	5.0	4.6	4.0
240	3.7	4.2	5.9	5.7	8.6	10.7	6.6	8.1	4.4	4.6	3.7	3.9

	Lime rates -- kg/ha --
L_0	none
L_1	4480
L_2	8960
L_3	13440

---

[1] Average data for 3 replicates.

Table 70.--Effect of lime and phosphorus fertilization on pangolagrass forage yields.[1]

P	1st harvest				2nd harvest				3rd harvest			
	L_0	L_1	L_2	L_3	L_0	L_1	L_2	L_3	L_0	L_1	L_2	L_3
kg/ha	g/pot											
PROFILE II												
60	0.6	0.6	0.7	0.7	2.6	2.3	2.7	3.6	2.7	1.9	2.5	2.1
120	0.8	0.3	0.5	0.6	1.5	1.9	2.5	3.7	1.5	2.8	3.3	3.5
180	0.5	0.5	0.3	1.0	1.9	2.4	1.8	2.6	2.4	1.3	2.1	3.4
240	0.4	0.8	0.4	0.8	2.3	2.8	3.1	2.7	2.4	1.5	1.7	3.6

	Lime rates -- kg/ha --
L_0	none
L_1	1680
L_2	3360
L_3	5040

---

[1] Average data for 3 replicates.

Table 71.—Analysis of variance for pangolagrass forage yields as affected by lime and phosphorus fertilization - Profile I.

Source of variation	Degrees of freedom	Mean squares	F
Replications	2	0.03	N.S.
Treatments	15	30.40	**
Lime	3	57.16	**
Phosphorus	3	76.58	**
Lime x Phosphorus	9	6.09	**
Error	30	1.10	

**Significant at 1% level.

Table 72.--Analysis of variance for pangolagrass forage yields as affected by lime and phosphorus fertilization - Profile II.

Source of variation	Degrees of freedom	Mean squares	F
Replications	2	0.29	N.S.
Treatments	15	3.58	**
Lime	3	11.47	**
Phosphorus	3	1.12	**
Lime x Phosphorus	9	1.76	**
Error	30	0.12	

**Significant at the 1% level.

Table 73.--Effect of lime and phosphorus fertilization on micronutrient concentration in pangolagrass forage.[1]

Applied Lime	Applied P	Zn	Mn	Cu	Fe	Al	Zn	Mn	Cu	Fe	Al
-kg/ha-		ppm									
		PROFILE I					PROFILE II				
None	60	121	505	22	48	165	126	447	16	36	50
	120	117	470	11	38	151	120	425	16	32	70
	180	113	390	12	39	127	115	380	16	32	80
	240	104	341	13	36	120	84	338	16	32	90
L_1	60	91	462	15	39	123	192	425	15	43	93
	120	114	455	20	40	125	175	430	10	39	86
	180	115	440	25	40	126	158	485	17	36	66
	240	102	472	17	36	134	149	472	17	36	66
L_2	60	78	330	17	33	140	166	322	16	35	83
	120	78	310	16	33	139	165	330	14	40	89
	180	77	305	16	35	139	167	355	12	45	150
	240	72	300	16	35	136	167	455	11	53	209
L_3	60	76	205	13	36	113	149	474	10	60	202
	120	72	205	10	35	119	148	490	12	50	190
	180	70	190	18	36	117	147	550	17	38	175
	240	69	178	23	45	116	145	650	10	36	166

Lime	Profile I	Profile II
	kg/ha	
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

Table 74.--Effect of lime and phosphorus fertilization on nutrient concentrations in pangolagrass roots.

Applied Lime	 P	P	K	Ca	Mg	P	K	Ca	Mg
--kg/ha--		%							
		PROFILE I				PROFILE II			
None	60	0.04	0.47	0.13	0.11	0.06	0.76	0.24	0.30
	120	0.04	0.22	0.12	0.10	0.12	0.35	0.33	0.26
	180	0.05	0.17	0.07	0.09	0.12	0.70	0.41	0.27
	240	0.05	0.27	0.09	0.09	0.18	0.86	0.51	0.30
L_1	60	0.04	0.38	0.19	0.09	0.12	0.85	1.41	0.35
	120	0.06	0.32	0.18	0.14	0.07	0.65	1.27	0.28
	180	0.05	0.31	0.15	0.10	0.13	0.51	1.08	0.23
	240	0.05	0.33	0.16	0.13	0.13	0.61	1.24	0.27
L_2	60	0.03	0.21	1.52	0.13	0.05	0.73	1.59	0.31
	120	0.05	0.25	1.32	0.14	0.12	0.79	1.44	0.31
	180	0.04	0.29	0.70	0.11	0.15	0.66	1.61	0.28
	240	0.06	0.27	0.41	0.09	0.20	0.76	1.45	0.27
L_3	60	0.04	0.37	0.51	0.08	0.08	0.94	1.03	0.23
	120	0.05	0.42	0.76	0.08	0.09	0.81	1.29	0.26
	180	0.06	0.48	0.47	0.09	0.14	0.73	1.71	0.28
	240	0.05	0.25	0.41	0.09	0.17	0.73	1.35	0.23

Lime	Profile I	Profile II
	----------kg/ha----------	
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

Table 75.--Analysis of variance for pigeon pea forage yields as affected by lime and phosphorus fertilization - Profile I.

Source of variation	Degrees of freedom	Mean squares	F
Replications	2	0.12	N.S.
Treatments	15	2.11	**
Lime	3	6.80	**
Phosphorus	3	1.83	**
Lime x Phosphorus	9	0.64	**
Error	30	0.11	

**Significant at the 1% level.

Table 76.--Analysis of variance for pigeon pea forage yields as affected by lime and phosphorus fertilization - Profile II.

Source of variation	Degrees of Freedom	Mean squares	F
Replications	2	0.06	N.S.
Treatments	15	0.47	**
Lime	3	0.99	**
Phosphorus	3	0.17	**
Lime x Phosphorus	9	0.40	**

**Significant at the 1% level.

Table 77.--Effect of lime and phosphorus fertilization on micronutrient concentrations in pigeon pea forage.

Applied											
Lime	P	Zn	Mn	Cu	Fe	Al	Zn	Mn	Cu	Fe	Al
--kg/ha--		ppm									
		PROFILE I					PROFILE II				
None	60	115	284	16	62	176	345	475	15	52	150
	120	119	286	13	98	179	462	497	18	44	119
	180	129	288	13	69	196	429	497	18	68	120
	240	119	269	12	97	224	506	487	24	77	126
L_1	60	48	125	18	59	126	193	426	16	55	80
	120	64	169	17	71	136	299	439	15	43	86
	180	58	113	16	60	137	314	491	19	46	124
	240	63	160	12	68	100	234	484	14	41	86
L_2	60	57	160	14	58	150	162	341	12	75	83
	120	61	153	16	53	80	154	386	11	38	118
	180	52	140	17	50	120	153	325	18	43	49
	240	50	147	8	55	80	182	386	11	44	93
L_3	60	50	123	28	52	80	148	440	12	36	79
	120	49	123	26	55	97	150	439	11	40	77
	180	56	126	23	53	100	158	366	19	41	62
	240	40	130	23	50	117	149	451	19	41	63

Lime	Profile I	Profile II
	---------kg/ha---------	
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

Table 78.--Effect of lime and phosphorus fertilization on nutrient concentrations in pigeon pea roots.

Lime	P	P	K	Ca	Mg	P	K	Ca	Mg
--kg/ha--		%							
		PROFILE I				PROFILE II			
None	60	0.09	0.30	0.29	0.12	0.23	2.02	0.31	0.45
	120	0.09	0.33	0.32	0.16	0.39	1.57	0.43	0.31
	180	0.11	0.31	0.30	0.16	0.54	1.08	0.46	0.26
	240	0.10	0.27	0.36	0.17	0.65	1.41	0.67	0.29
L_1	60	0.08	0.26	0.73	0.15	0.18	2.41	1.73	0.40
	120	0.12	0.29	0.76	0.16	0.35	1.58	1.70	0.31
	180	0.15	0.35	0.75	0.21	0.45	1.77	1.74	0.34
	240	0.12	0.30	0.72	0.17	0.52	1.26	1.85	0.33
L_2	60	0.09	0.51	0.95	0.15	0.15	2.06	2.37	0.37
	120	0.12	0.51	1.00	0.17	0.18	1.87	2.47	0.41
	180	0.15	0.47	1.04	0.18	0.28	2.11	2.43	0.39
	240	0.16	0.35	1.00	0.22	0.22	1.84	2.79	0.40
L_3	60	0.09	0.51	1.00	0.17	0.12	2.25	2.42	0.39
	120	0.14	0.32	1.13	0.16	0.13	2.78	2.52	0.36
	180	0.16	0.35	1.08	0.16	0.18	2.06	2.87	0.40
	240	0.17	0.42	1.21	0.19	0.22	1.83	2.60	0.39

Lime	Profile I	Profile II
	kg/ha	
L_1	4480	1680
L_2	8960	3360
L_3	13440	5040

Table 79.--Description of soil profiles.

Depth -- cm --	Characteristics
	PROFILE I
0-15	Dark brown (10 YR 3/3), changes to black when wet. Humic, clay loam of aggregate structure. The consistency is sticky and plastic when wet, friable when moist and dry. Abundant grass roots. Thick superficial stolon-root mat and litter layer.
15-27.5	Dark gray (7.5 YR 4/3). Less humic. Structure is fine to medium crumb. Consistency is sticky and plastic when wet, friable when moist and dry. Yellow and red mottlings are noticeable; slight gley features.
27.5-37.5	Brownish yellow (10 YR 6/8). Texture is clay of fine crumb structure. Very sticky and plastic when wet. It sets hard when dry. Abundant gray gley and yellow and red mottlings.
37.5-90	Reddish-yellow (7.5 YR 6/6). Texture is clay. Structure is rather angular, blocky. Very sticky and plastic when wet. It sets very hard when dry. Abundant gray gley and mottling features.

Main features

1) Highly humic surface horizon with abundant grass roots.

2) Drainage impeded.

3) Abundant hydromorphic features below 15 cm depth layer.

4) High water table, within 37.5-90 cm depth layer. Water trickled constantly from sides and bottom of pit.

Table 79.--Continued

Depth -- cm --	Characteristics
	PROFILE II
0-15	Light grey (10 YR 7/2). Sandy loam. Fine single grain structure. Non-sticky and non-plastic when wet. Loose when dry and moist. Sparse litter and grass roots.
15-30	White (2.5 YR 8/2). Sandy loam, finer than previous horizon. Otherwise same characteristics.
30-45	Yellow (10 YR 7/8). Sandy loam. Change in consistency to slightly plastic and sticky when wet, firm when moist and sets hard when dry, denoting strong cementation.
45-60	Change to more compact. Otherwise similar characteristics as above horizon.
60-90	Change to less compact. Sides of the pit slipped down easily. Water trickled constantly from sides and bottom of pit.

Main features

1) Uniform sandy loam texture.

2) Presence of compacted layer between 30 and 60 cm depth.

3) Drainage imperfect.

4) Presence of hydromorphic features below 15 cm depth horizon. Grey gley was noticeable below 60 cm depth horizon.

5) High water table at time of sampling. It was within the 60-90 cm depth horizon.

SUMMARY AND CONCLUSIONS

Puleton soils from the Coastal Pine Ridge region of British Honduras were investigated. The study comprised three main phases, namely, field work, laboratory studies, and greenhouse investigations.

Two sites were selected in the Belize area. Each comprised soils of different textural properties and were identified as Profiles I and II throughout the text. These soils covered a total area of 36,721 ha in the country. Approximately 70% of that area is concentrated close to Belize City. Additional soil samples were taken at different locations comprising other Puleton soils, primarily for laboratory analyses.

Field observations, made at the time of sampling, revealed that both soils were affected by poor drainage conditions. Typical hydromorphic features below the surface soil were common. Waterlogging of these soils was possibly caused by high subsoil clay content in Profile I, and by compaction due to predominance of fine and very fine sand, particularly in the 30-60 cm depth horizon, in Profile II.

Mechanical analysis identified the Profile I surface soil as clay loam, and the Profile II surface soil as sandy loam. The Puleton soils which cover about 80% of the total pine ridge area (2,849 km^2) were coarse textured, namely, sandy loam and sandy clay loam. About 20% comprised clay loams and clays. The dominant clay mineral was kaolinite, which indicated that these soils were highly weathered and in an advanced stage of maturity.

In general, pH of the Puletan soils was medium-low to very low. It ranged between 4.7 and 5.6. pH values most likely reflected climatic conditions and type of soil parent material. Organic matter in most of the soils ranged from medium to low. It diminished with depth. Profile I contained more organic matter in the surface horizon than Profile II, namely, 5.9 and 1.6%, respectively.

Nitrogen concentrations, in general, were also low and reflected the organic matter concentrations. The C/N ratios in the majority of the soils were above the value of 10, particularly in surface soils.

Total, organic, and Truog's available P were generally low. Profile I soil horizons had higher concentrations than those from Profile II. The absence of P-bearing minerals in these soils indicated the possibility that the greater part of the soil P was derived from readily mineralizable organic materials. Base saturation and CEC were also low due to low organic matter, predominance of kaolinitic clay, high Al concentration, high intensity of weathering and of leaching, and predominance of sand size textured constituents. Exchangeable Ca, K, and Mg were low. Relative ratios showed the existence of marked imbalances among these three nutrients. In Profiles I and II, exchangeable Ca appeared to be higher in the subsoils than in the surface soils. This indicated the possibility of an enrichment by Ca-charged ground water. Exchangeable Na was relatively high in both soils. The high Na concentration, particularly in the lower layers, may enhance soil compaction due to its detrimental effect on soil structure.

There were no standards by which micronutrients and total cation concentrations could be evaluated. However, chemical analyses of the Puleton soils revealed their low potential to produce crops without fertilization, especially in terms of P.

Horizons from Profile 1 showed higher P fixing capacities, as expected from their physical and chemical properties, than horizons from Profile II. Lime had limited effect on P fixation in Profile I. High rates of lime, 4000 kg/ha, decreased P fixation. In both soils, most of the retained P appeared as Al-P due to type of clay and to highly reactive Al present in amorphous minerals. High organic matter concentration may have been an additional factor in the case of soils from Profile I.

The rate at which P was fixed in soils from Profile 1 appeared to be high as indicated by laboratory studies made with sulfur-absorption tubes. Unlimed and limed soils fertilized with 60 and 120 ppm P in the form of finely ground triple superphosphate mixed in the surface were placed in the tubes. Leaching was simulated with distilled water. Surface soils and simulated profiles were used. In the latter, variable amounts of soil from the different horizons were placed in order in the tubes. The amount of P recovered in the leaching was very low, approximately 1% or less of the total P applied, from the surface soil or simulated Profile I. Most of the P was fixed in the top 4 cm of soil. Although the amount of P recovered in the leaching was low, lime did increase significantly P in the leaching.

Similar treatments were applied to unlimed and limed soils from Profile II. The amount of P leached was much higher than from Profile 1. Approximately 94 and 70% of applied P was leached from unlimed and limed surface soils, respectively. These results showed the beneficial effect of lime on P retention in sandy textured soils. Leaching of P from the simulated profile was approximately 10% and 7% from unlimed and limed soils, respectively. While in Profile I, most of the P was retained in the surface layer with the remainder in the next two lower layers, the reverse occurred in Profile II. Only 17 and 28% was retained in the surface unlimed and limed layers, respectively. The majority of the P in Profile II, 41 and 36% for unlimed and limed material, respectively, was retained in the 60-90 cm depth, which was represented by the bottom layer. The remainder was fixed in the intermediate horizons in relation to their clay concentrations.

Greenhouse experiments using the tomato as the first indicator plant emphasized the need for fertilizer applications in order to make these soils productive. In both soils, negligible yields were obtained when fertilizers were omitted. By contrast, yields where P was applied, were more than 50 times these without P. Response to applied N and K, alone or in combination, was small. Both, separately or combined in the presence of P, gave large responses, frequently above those obtained with P alone. In most cases the combination NPK gave highest yields, particularly in Profile II surface soils. In both profiles there was a positive, significant response to lime. However, the highest lime level used in Profile I surface soil, 4480 kg/ha, had an apparent detrimental effect on the NP and NPK treatments. This decrease in yields was inexplicable and it did not occur in subsequent experiments with similar treatments. In both soils yields were consistently higher from surface than from subsoils.

In general, plant nutrient concentrations were increased significantly by fertilization. Plant Ca concentration was the most variable as affected by rate of lime. Phosphorus and Ca concentrations were in agreement with those reported in Florida for the tomato (69). Phosphorus deficiency was very striking in plants growing in absence of this nutrient. Presumably N and K were adequately supplied since no deficiency symptoms were noted. Deficiencies of Mg and micronutrients were not observed. These elements were applied to all pots as a uniform treatment.

The effect of lime and fertilization on tomato root growth was similar to that on foliage. Root proliferation in the presence of P fertilizer was tremendously increased compared to growth without P. Nutrient concentrations in tomato roots were also significantly increased by fertilization and followed the same trends as for the foliage.

The effect of fertilization on yields of the subsequent crop, pangolagrass, followed the same tendency as on tomato plants. Yields were very low in the absence of P and were increased significantly by applied P. Yields from the second pangolagrass harvest were lower than from the first. Deficiencies of N and K apparently accounted for reduced yields since deficiency symptoms of these nutrients were common in all treatments after the first harvest. Additional N and K applications in amounts equivalent to the original quantities were made to appropriate treatments.

Potassium and Ca, in addition to P, appeared to play an important role in forage production. Decrease in plant K concentration in the second pangolagrass harvest was accompanied by an increase in plant Ca concentration. Lime may have enhanced the imbalance of soil Ca and K, and uptake of the latter may have been supressed by Ca. Response to P application was large and was reflected in length and number of stolons per pot. When P was present, there were 5 to 6 stolons per pot at harvest time, many as long as 2.5 cm. Without P there were usually not more than 1 or 2 stolons of approximately 10 cm length. The effect of fertilizers on root growth was similar to the effect on forage production. Root nutrient concentrations were also similarly affected.

The growth of hairy indigo as the third crop, with the same soil and without replenishment of P fertilizer, was relatively poor. Plants were small in size and P deficiency was common to all treatments. Based on plant P concentrations of approximately 0.67% found in Florida (150) it appeared that the P requirement of hairy indigo was relatively high and was not satisfied by the residual applied and soil P after two other crops had been grown. Phosphorus recoveries by the previous two crops exceeded 50% of that applied. Nodules were not present on indigo roots despite the application of inoculum after seeds had germinated. Possibly the method of inoculation was not effective. Root growth was very poor and followed the same tendency shown by the forage. In general the effect of lime both on the forage and root growth was irregular as compared to previous crops.

A second experiment was conducted in which lime and P were applied at 4 rates each with a basic application of other macro-and micronutrients. Only surface soils were tested. Pangolagrass was planted first. In Profile I, lime at the rate of 4480 kg/ha gave the highest yields. Plant P concentrations increased with rates of applied P regardless of lime rates. From the three harvests obtained, the second produced the largest yields. Shortage of soil K relative to Ca and Mg may have caused a decrease in yields. In fact, plant K concentrations decreased noticeably from 2.5% at the first harvest to less than 2% at the third harvest. Forage Ca concentrations increased with rates of lime. Yields were lower from Profile II than from Profile I. Lime and P responses were positive and statistically significant. Yields also decreased at the third harvest. At this stage, N and K deficiencies were common in almost every treatment. Additional N and K fertilizers were applied, but the time of application may not have been sufficiently soon to prevent yield decreases. Micronutrient deficiencies were not noted. Concentrations found in the forage were rather high. Root growth and nutrient concentrations were lower than for forage, but followed the same trend in their responses to fertilization.

The residual lime and fertilizer effects were tested with pigeon pea. In Profile I, lime and P fertilization significantly increased yields. Plant P concentrations were almost the same regardless of the rate of lime applied. Potassium concentrations increased and were higher than Ca and Mg at highest lime rates. These fluctuations of plant nutrient concentrations were doubtless due to K addition to the soil prior to the third harvest of the previous pangolagrass crop, which may have supressed Ca and Mg uptake by the forage. In general, yields from Profile II were lower than from Profile I. Plant nutrient concentrations followed the same trends shown by Profile I. The effects of lime and applied P on root growth were similar to the effects on forage. Micronutrient concentrations were relatively high in the forage.

Conclusions warranted by the data from these investigations are as follows

1) Field observations and results of physical analyses indicated that both soils were affected by poor internal drainage due to high clay content or compaction, mainly below 30 cm depth.

2) The natural soil fertility was very low, particularly with respect to P. There appeared to be an imbalance among Ca, Mg, and K; however, plant yields were increased as much as 50 times by P fertilization. Root proliferation was increased similarly. Yields were further increased by addition of N and K. Response to N and K, applied singly or together, was negligible. There was a positive yield response to lime in both soils. Data indicated that 4500 kg/ha of calcium carbonate was adequate in both soils.

3) When these soils were adequately limed and fertilized, plant concentrations of P, K, Ca, and Mg appeared to be within established ranges for optimum plant growth and animal requirements. Examination of differential response to micronutrients was not attempted, but small additions of Mn, Zn, and Cu provided adequate concentrations of these elements in pangolagrass and pigeon pea forages.

4) Lime appeared to have opposite effects on P retention in these soils. While P retention was decreased slightly by lime in Profile I, it was increased markedly in Profile II. Increased retention in Profile II may be beneficial in practice. However, movement of applied P from the surface soils probably will not be critical, since in both, the majority of applied P was retained in the 0-30 cm depth which is within the normal rooting zone of the majority of crop and pasture plants.

5) The potential for development of the Puletan soils was demonstrated. Satisfactory yields were obtained where P rates between 150 and 240 kg/ha were applied with N and K. The residual P effect extended for 6 to 10 months after P application, through one tomato and 2 to 3 pangolagrass crops grown successively.
6) The subsoils of both profiles proved to be less fertile than their respective surface soils. However, response to fertilization, especially with P, followed the same trend shown for the surface soils.
7) Further studies are needed to establish the most suitable method to correlate soil P with crop yields after fertilizer P is applied.
8) Suitability of the Puletan soils appeared to be favorable for a diversity of crops, pastures, and reforestation. Construction of an adequate surface drainage system would be most beneficial if these soils are to be cropped. In the case of Profile II, mulching for arable crops should be practiced to prevent lateral erosion and to increase its present low water holding capacity and low colloidal content.
9) Initial cost of developing these soils may be low since no major clearing operations would be required considering the low, sparse vegetation, as compared to more fertile, heavily forested soils.
10) Study of legumes is needed due to the low native soil N, slow N mineralization and the high cost of N fertilizers. Additional information concerning the adaptation of grasses would also be beneficial.

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BIOGRAPHICAL SKETCH

Rufo Bazan was born on February 28, 1929, at Potosi, Bolivia. In 1945, he graduated from The American Institute in La Paz, Bolivia, and obtained the degree of Bachelor in Humanities. From 1946 to 1951, he attended the School of Agronomy of the University of San Simon, in Cochabamba, Bolivia, and of the Rural University of Rio de Janeiro, Brazil, where he was graduated and obtained the degree of Ingeniero Agronomo, in November, 1951.

From January, 1952 to August, 1956, he worked on his own farm in Santa Cruz, Bolivia. From September, 1956 to June, 1961, he worked as agricultural technician in the InterAmerican Agricultural Service, Supervised Agricultural Credit Program, in Bolivia, successively as County Supervisor and Regional Assistant Director, in Santa Cruz, and as National Technical Inspector, in La Paz. In June, 1961, he was admitted to the Graduate School of the InterAmerican Institute of Agricultural Sciences, in Turrialba, Costa Rica, in the Plant Industry and Soils Department. His studies on cacao soils were directed by Professor Frederick Hardy. He graduated and obtained his degree of Magister Agriculturae in June, 1963.

From September, 1963 to April, 1964, he worked for Standard Fruit Co., Research Department, in Costa Rica, as Soil Scientist. In May, 1964, he joined the staff of the InterAmerican Institute of Agricultural Sciences, in Turrialba, Costa Rica, as Junior Soil Scientist and full-time assistant to Professor Frederick Hardy.

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Rufo Bazan is married to the former Maria L. Covarrubias. They have three children, Fernando, Roberto, and Maria Patricia. He is a member of Sigma Xi honorary fraternity, American Society of Agronomy, and Soil Science Society of America.

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This dissertation was prepared under the direction of the chairman of the candidate's supervisory committee and has been approved by all members of that committee. It was submitted to the Dean of the College of Agriculture and to the Graduate Council, and was approved as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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